11 Recirculating Aquaculture System for Intensive Fish Farming in Indian Himalayan Region: An Overview

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Abstract

In this era of increasing population, food supply challenges, environmental sustainability concerns and limiting natural resources, fish farming is globally moving towards land-based recirculating aquaculture systems and technologies that could produce traceable, safe and healthy fish and seafood. Recirculating aquaculture system (RAS) is a resource-efficient and climate-resilient technology in which the dependence on water, land and climatic factors is substantially minimized. As the name suggests, RAS works on the principle of reusing the culture water after various levels of filtration, targeting to provide optimum water conditions for better fish growth and welfare. This chapter provides an overview of a RAS, including its rationale, advantages, design aspects, water quality requirements, RAS components/equipment, operational management of the system and challenges and opportunities in adapting this aquaculture technology with particular reference to cold-water fish culture.

Keywords

Recirculating aquaculture systems · Water quality requirements · Total suspended solids · Settling unit · Dissolved oxygen

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11.1 Introduction

Over the last three decades, fish production from capture sources has stagnated at around 80 million metric tonnes (mmt). Nevertheless, during the same period, global fish production increased from 101 to 178.5 mmt, mainly due to the expansion and advances in aquaculture practices. According to FAO, aquaculture alone contributed 114.5 mmt, including 82.1 mmt of aquatic animals in 2018 (FAO 2020). Several aquaculture practices such as pond aquaculture, cage, pen culture, flow-through system and in-pond raceway systems (IPRS) are being used to extensively or semi-intensively or intensively farm aquatic animals on large scales. Intensive aquaculture practices have lately come under the radar of environmental sustainability issues, for example, clearing of mangrove forests for coastal aquaculture, converting agricultural lands into aquaculture ponds, effluent discharge, disease outbreaks and transmission of diseases to the natural or wild population (in the case of cage culture) and biodiversity issues and decline of the natural population (when exotic fish and shellfishes are introduced to enhance productivity). In this context, expansion and annual growth rate of aquaculture is expected to decrease from the current rate of 4.3% to 2.3% during 2018–2030 (FAO 2020). Furthermore, aquaculture activity is limited due to strong enforcement of environmental regulations, competition for limited resources (especially for the use of water and land by other food-producing sectors and industries), urbanization, disease outbreaks due to intensive culture practices and increasing consumer awareness towards safe and sustainable aquaculture products. Therefore, farming fish in a sustainable way is the only option to meet the future fish and seafood demand to achieve global nutritional security (Naylor et al. 2021).

Recirculating aquaculture system (RAS) is recognized as one of the most sustainable aquaculture technologies (Naylor et al. 2021), where aquatic animals are cultured either in partially or completely controlled conditions, in high densities, with the reuse of water after removing faecal waste, ammonia, carbon dioxide and addition of oxygen. The water recirculation efficiency varies from 70 to 99.5% depending on the filtration system in place (e.g. 70% in a partially recirculating system to 99.5% in a completely circulating system where water required can be as low as 0.3 m^3/kg fish) (Timmons et al. 2018; Bregnballe 2015; Espinal and Matulić 2019). RAS is considered environmentally sustainable and offers several advantages over the current aquaculture practices, such as low water and land requirements, high unit productivity, resilience to weather and climate change and effective control of farm effluent discharges (detailed comparative advantages are provided in Table 11.1).

Table 11.1 Advantages of recirculating aquaculture system over traditional aquaculture practices

• 10–100 times reduction in water usage (in the case of rainbow trout, 0.5–1 m^3 water is required per kg of fish produced in RAS, compared to 50–120 m^3 water requirement in flow-through system)
• 3–10 times lower land footprint (in intensive pond aquaculture, to produce 40 tonnes of fish, 1 ha of the land area is required. But the same can be achieved in RAS with less than 0.1 ha of land area)
• Faster growth rates due to controlled conditions (in the case of rainbow trout, 5–6 months of crop duration in RAS compared to 10–14 months in flow-through system)
• RAS also makes aquaculture possible in places where conditions are naturally not conducive, in terms of water availability and climatic conditions (e.g. unsuitable lands for agriculture, near to the market, hot or cold arid desert. Salmon and yellow tail are produced in Middle East countries, and tilapia, shrimps or warm-water fishes are cultured in the cold regions of the world in RAS)
• Resilient to weather and climate change
• Better feed efficiency and reduced feed cost due to controlled conditions
• Proper health management due to better water quality control and easier biosecurity measures
• Lower eutrophication potential as concentrated effluent can be easily treated
• Easy nutrient valorisation is possible through the utilization of sludge/effluent for biogas and bio-fertilizer production
• Integration with agriculture to utilize nitrate-rich wastewater can reduce fertilizer requirements in agriculture
• Aquatic invasion and escape of exotic fishes can be curtailed due to controlled operations
• Reduced labour costs and fish can be sold as per the market demand

11.2 More Crop Per Drop and RAS as a Climate-Smart Farming Solution to Productivity and Production Issues

In pond aquaculture practice, the biological productivity (in terms of fish production) of a pond is limited (0.4–1 kg fish/m^3) by dissolved oxygen availability (and diurnal dynamics of dissolved oxygen in a pond), while additional aeration can enhance the fish productivity to 4 kg/m^3 of water. Nevertheless, further productivity enhancement is limited by waste (faecal matter) and metabolite (ammonia) accumulation that necessitates water exchange, resulting in effluent discharge issues. To overcome the increased requirement of dissolved oxygen and flushing of the metabolites and waste generated, a flow-through system is used to culture certain fishes (e.g. rainbow trout, a cold-water fish), where productivity can be achieved >30 kg fish/m^3 of water. However, this results in a large volume of dilute effluent discharge, and this practice entirely relies on a continuous supply of good quality natural water resources (requiring 50–120 m^3 of water flow for every kg fish, produced in the case of rainbow trout). Besides, these systems are vulnerable to extreme weather events and adverse changes in water quality/quantity during floods and landslides, as raceways are normally located near streams and rivers. In the case of RAS, the above issues are taken care of through a systematic series of inline treatment procedures, enabling higher fish productivity in the range of 60–120 kg/m^3 of water. In RAS, fishes are reared in separate culture tanks, which are connected to a

Fig. 11.1 Major components of a commercial recirculating aquaculture system (RAS) loop

series of filtration systems and equipment, such as mechanical filters (to remove solids), biological filters (to remove ammonia, nitrite and nitrate), disinfection units (to reduce pathogenic microorganism load), degassing and oxygenation units (to remove CO_2 and nitrogen and to add oxygen in the system) and pumps (to pump the water back to fish rearing tank) (Timmons et al. 2018; Bregnballe 2015). A commercial RAS loop is depicted in Fig. 11.1.

11.3 Things to Consider Before Starting Fish Farming in RAS

Like any other farming activity, the first thing before starting up a RAS is to choose a suitable fish species depending on the market survey (e.g. demand in the local and international market) and the availability of good quality fish seed and feed. Generally, the culture of premium or high-value fish (INR > 500 or US $ 6.5) is profitable in RAS, considering the electricity cost and initial investment. Once the species is decided, the scale of operation and production targets is set before the RAS design is prepared. In the current chapter, rainbow trout is considered as an example as it is a high-value cold-water aquaculture species in India and across the globe.

Designing a RAS system primarily involves several calculations and requires estimates on paper or in excel. This includes aspects such as water flow rate, accordingly choice of pump, sizing of fish tanks, mechanical filter, the volume of biological filter, degassing, aeration and oxygenation capacity, plumbing and total area required for all the operation and building specifications required to produce a given quantity (in tonnes) of fish. A good RAS design aims to provide optimum water quality for fast growth of the fish with minimum operational cost and complexity. RAS designing also provides a basic idea of the budget required and the projects economic viability. Once the project is convincing, the blueprint is prepared, and the project is executed.

11.4 Principle for the System Design

A grow-out RAS aims to grow and produce fish that requires optimal feeding. Only a portion of the feed is converted into fish muscle, and the rest is excreted as faeces, ammonia and carbon dioxide. As Fig. 11.2 depicts, when a kg of feed (42–45% protein and 16–20% lipid) is fed to rainbow trout, only 70–75% of the consumed feed is digested. The remaining 25–30% is excreted as faeces, contributing to the total suspended solids in the fish tank. Further, as fish utilizes amino acids for energy production, ammonia is excreted, corresponding to the protein content of the feed (i.e., the TAN = protein content of a feed multiplied by 0.92; if the protein content is 45%, the TAN produced will be around 41.4 g/kg feed). Similarly, 0.4 kg of carbon dioxide is produced for every kg of feed metabolized, relative to oxygen consumption. Fish also requires nearly 0.3 kg of oxygen to metabolize every kg of feed. Accordingly, based on the maximum feed consumed during the production cycle, the water flow rate is calculated, and different filtration systems are designed to flush and remove/detoxify waste before the water is recirculated. It should also be kept in mind that the above values may change depending on the species and quality or composition of feed, e.g. tilapia requires low protein feed (35%). A good quality feed that meets all the nutritional requirements of the fish, with high digestibility and faecal decantation rate, is, thus, a prerequisite for the success of RAS operation.

11.5 Water Quality Monitoring and Management

Though water requirement in RAS is much less than conventional aquaculture production systems, water is still required to fill the system initially and for daily exchange and makeup 5–20% of the system volume. This quantity depends on the system's hydraulic retention time or recirculation efficiency, which in turn depends on the efficiency of filtration and the kinds of filtration in place. On the other hand, the physical and chemical quality of source water (especially temperature, dissolved oxygen, nitrogen, carbon dioxide, pH, hardness, fluorides and heavy metals) needs

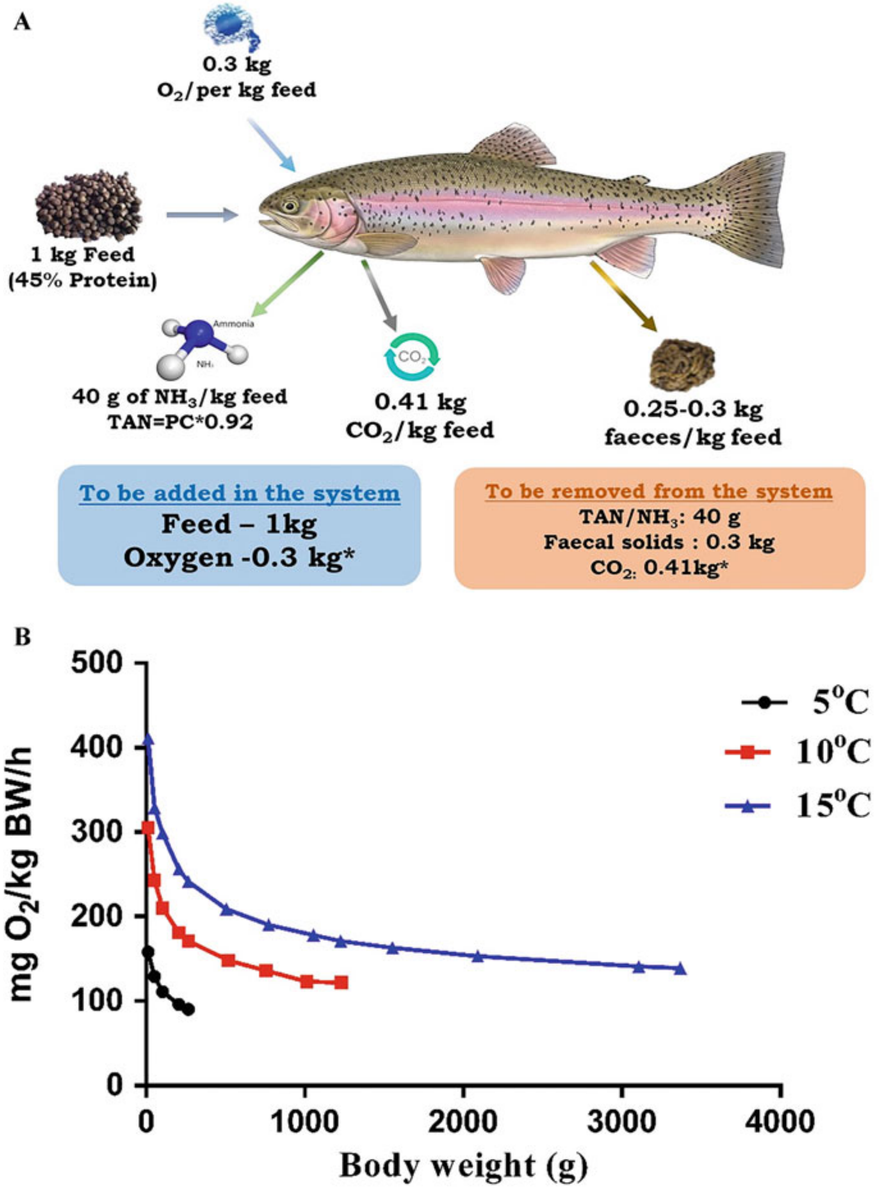

Fig. 11.2 (**a**) A schematic mass balance diagram of feeding fish in RAS. PC, the protein content of feed; faecal matter is given on a dry matter basis (on wet basis, it will be 1.25–1.5 kg faeces/kg dry feed). (**b**) The size and temperature-specific estimated oxygen consumption in rainbow trout. With increasing rearing water temperature, oxygen consumption increases, and similarly, oxygen consumption decreases with increasing body size (Cho and Bureau 1998)

Table 11.2 Optimal water quality requirement for fish farming in RAS (adapted from Timmons et al. 2018)

Parameters	Rainbow trout	Tilapia
Temperature (°C)	12–18	25–30
Dissolved oxygen	>80% saturation	>80% saturation
Dissolved oxygen (mg/L)	6–9	4–6
Dissolved oxygen at outlet (mg/L)	≥ 5	≥3
Ammonia ($NH_{3.}$ N) (mg/L)	<0.02	<0.6
TAN(NH_3 + NH_4) (mg/L)	<1	<3
Nitrite (mg/L)	<0.5 or 0.1 (soft water)	<1
CO_2 (mg/L)	<20	<40
Alkalinity (mg/L)	50–300	50–300
Nitrate (mg/L)	0–400	0–400
pH	6.5–8.5	6.5–8.5
Phosphorous (mg/L)	0.01–3.0	0.01–3.0
TSS (mg/L)	10–20	20–30
Hardness (mg/L)	50–300	50–300
Chloride (mg/L)	>200	>200
Ozone (mg/L)	<0.005	<0.005

to be checked for suitability. Generally, groundwater is suitable for RAS application as it provides enough alkalinity and is usually free from pathogenic microorganisms. Open-source water drawn from springs, rivers, sea and lakes may require disinfection before use and the addition of alkalinity. The following table (Table 11.2) summarizes the conducive range of water quality parameters that need to be maintained for the optimal growth and welfare of a cold-water and warm-water fish (rainbow trout and tilapia). These values are targeted to achieve while designing a RAS (species specific).

11.5.1 Temperature

Though fishes have a broad temperature tolerance range, the optimum range for growth or reproduction (production traits) is very narrow and is species- or strain-specific. For example, for rainbow trout, 12–18 °C is considered an optimum range for growth, while for reproduction, it is 8–12 °C. Narrowing further, the maximum feed utilization is observed at 1618 °C (Molony 2001). So in RAS, it is good to maintain a temperature of 16–18 °C by heating or cooling the water to achieve maximum fish growth. However, the economic benefits of heating or cooling need to be evaluated as long as fish are in their broader optimum range. It should be kept in mind that temperature is also an essential parameter for the performance of a biological filter. Low temperature decreases the performance of the biological filter; at temperatures below 8 °C, the biological filter becomes least functional. In our experiments, we have observed that at 6 °C, the biofilter ceases to function (Rajesh et al. unpublished data).

11.5.2 Dissolved Oxygen

Dissolved oxygen (DO) is the most critical parameter, and the adverse changes in their levels can lead to fish mortality within minutes when fish are reared at high density. Such events generally happen due to the break-down of equipment, efficiency reduction or power failure. Thus, a backup arrangement is essential for maintaining the desired oxygen level at all times. It is one such parameter which needs to be measured at least twice daily or continuously monitored. DO is mainly supplied in the water flow through external oxygenators or aeration devices; sometimes, aeration is also provided in the fish tank. Oxygen levels in the tanks should be always above 80% saturation, e.g. for salmonids, it should be >6 mg/L and tilapia >4 mg/L all time (Timmons et al. 2018). The dissolved oxygen level in the outlet should not be below 5 and 3 mg/L for salmonids and tilapia, respectively. Feed intake ceases at the DO level < 4.5 mg/L, in the case of rainbow trout. The dissolved oxygen consumption pattern in rainbow trout is depicted in Fig. 11.2b; it increases with rearing temperature and decreases with body size. Thus, the juveniles require higher dissolved oxygen than the table-sized fish for given biomass, and the juvenile fish need to be stocked at a low stocking density (in terms of biomass or kg/m^3).

The saturation levels of DO decrease with increasing altitudinal location above the mean sea level (or with lowering of partial pressure of oxygen). For example, at 100 m.s.l. altitude at 15 °C, DO saturation value is 9.97 mg/L, and at 1500 m.s.l., DO saturation level is 8.39 mg/L. Likewise, oxygen solubility decreases with temperature. For example, at 10 °C, the saturation of DO is 11.28 mg/L at sea level, and at 25 °C, it is 8.26 mg/L (DO ⇆ % Saturation Calculator; waterontheweb.org). This is very important because, at high temperatures, the increased oxygen demand of fish coupled with low DO saturation levels can result in significantly lower growth and survival. On the contrary, when pure oxygen is used as a source for oxygenating the water, DO levels can be supersaturated (~40 mg/L), which is required for sustaining standing biomass of >35 kg/m^3 (Timmons et al. 2018; Summerfelt et al. 2000). It should also be kept in mind that even biofilter requires oxygen to carry out nitrification (i.e., conversion of ammonia to nitrate). Every gram of ammonia nitrogen requires nearly 5 g of oxygen for its oxidation into nitrate, so DO in biofilter should be above 2 mg/L all the time. Further, it is also essential to avoid anoxic zones in the system; an anoxic zone with the accumulation of organic matter could produce H_2S and eventually kill the fish. There are few reported cases of large-scale fish mortality due to H_2S toxicity in commercial salmonid RAS.

11.5.3 Carbon Dioxide

Carbon dioxide is generated in the system due to the respiration of fishes and bacteria. Carbon dioxide is also a part of the complex equilibrium in water, with carbonate and bicarbonate ions. Although different values are reported for carbon dioxide toxicity, the carbon dioxide concentration for rainbow trout should not be more than 20 mg/L. Further, the toxicity of CO_2 apparently increases with reducing pH and at low dissolved oxygen levels (3–5 mg/L) (Lloyd and Jordan 1964). Prolonged high CO_2 levels may also lead to the development of nephrocalcinosis, and this is also associated with the use of agriculture lime as an alkalinity source (Timmons et al. 2018). Generally, carbon dioxide is not an issue when aeration is used for oxygen supply, as aeration strips out carbon dioxide. However, when pure oxygen is used to improve dissolved oxygen at high stocking densities, carbon dioxide levels in water can go high, thus requiring a carbon dioxide stripper or degasser unit (Summerfelt et al. 2000; Colt et al. 2012).

11.5.4 Ammonia

Ammonia is the primary nitrogenous excretory product, generated from protein and nucleotide metabolism in fish, and it is excreted mainly through the gill. The toxicity of ammonia is pH- and temperature-dependent. As pH decreases towards the acidic range, most ammonia is converted to ammonium (NH_4^+) form, but as pH increases, most ammonia is transformed to free form or unionized form (NH_3). For instance, at the TAN value of 5 mg/L at 15 °C, the free ammonia fraction is 0.0165 mg/L, which is below the toxicity level. But at pH 9, free ammonia increases to 1.3 mg/L, which is highly toxic. As free ammonia can easily pass through fish gill by simple diffusion, it is toxic at very low levels (0.02–0.6 mg/L) as compared to ionized form, which cannot enter the gill (Ip and Chew 2010). Most ammonia test kits measure total ammonia nitrogen, abbreviated as TAN, as only nitrogen molecular weight is considered for standard. To get absolute total ammonia value, TAN must be multiplied by 1.21 (i.e., $NH_3 + NH_4^+ = TAN * 1.21$). When TAN, pH and temperature are known, both fractions and concentrations of NH_3 and NH_4^+ forms can be individually calculated from the NH_3-NH_4^+-pH-temperature tables or online software (e.g. Free Ammonia Calculator (JavaScript) (iastate.edu)). Allowed TAN concentration in RAS is 1 and 3 mg/L for cold- and warm-water fishes, respectively (Timmons et al. 2018).

11.5.5 Nitrite and Nitrate

Nitrite is an intermediate product of nitrification. Nitrite spike in RAS is observed due to several reasons such as immature biofilter (during the initial period of RAS operation), insufficient biofilter surface area, application of therapeutics against infection (e.g. formalin, hydrogen peroxide, etc.), disruption of water flow due to power/pump failure, ozone failure and increased total suspended solids due to inefficient solid removal. Ammonia and nitrite spikes generally do not occur in well-designed and matured biofilters (adequately designed based on the daily feed loading) and when DO levels in the biological filter are sufficiently high (>2 mg/L). Toxic nitrite levels convert haemoglobin to methaemoglobin, reducing its oxygen-carrying capacity and thus causing physiological hypoxia. The toxicity level of nitrite varies from 0.1 to 1 mg/L depending on the species. Nitrite toxicity can be reduced by adding chloride ions (NaCl); this neutralization requires nearly 20 times chloride ions for every mg/L of nitrite (cautionary note: chloride ions should not be confused with chlorine). Marine fishes are therefore more tolerant of high nitrite levels. Generally, in RAS, it is advisable to maintain 200 mg/L of chloride ions in water to prevent stress due to sudden spike in nitrite and also for other osmoregulatory benefits of NaCl. Nevertheless, the application of chloride ions to overcome nitrite toxicity is the only temporary or quick-fix remedy in RAS. But, for the long-term success of RAS operation, the reason for the nitrite spike must be identified and addressed with proper solution. During nitrite spike, exchanging water and stopping feeding is also advisable to prevent further building up of nitrite. In contrast, nitrate is the end product of biological nitrification and is not toxic even at high levels (>500 mg/L). Some studies have reported feed intake reduction due to high nitrate levels. Nitrate levels in the RAS are generally reduced by water exchange or through the denitrification process (Timmons et al. 2018).

11.5.6 Total Suspended Solids

For the success of RAS operation, controlling total suspended solids (TSS) is very important. If a proper solid removal system is not in place, TSS can go very high, especially when feed loading is high with increasing standing biomass. Every kg of feed generates nearly 0.25–0.3 kg of dry solid or 1.3–1.5 kg of wet solids. TSS levels above 20–30 mg/L are not suitable for the operation of RAS (Timmons et al. 2018; Couturier et al. 2009). High TSS may not kill fish immediately, but they reduce the efficiency of the biological filter, carbon dioxide stripping, oxygenation and UV filter and increases ozone dosage requirement. Further, they cause irritation in gills and reduce the visibility in water for fish and operators, resulting in difficulty in feeding and removing dead fish. This ultimately leads to the reduction of feed efficiency and further deterioration of water. High TSS favours the growth of geosmin and 2-methylisoborneol (MIB) producing bacteria and pathogenic bacteria, causing off-flavour and disease outbreaks in cultured fish, respectively. High TSS also favours the formation of anoxic zones resulting in the production of toxic hydrogen sulphide (H_2S).

11.5.7 pH, Alkalinity and Hardness

The pH of the water should be around 6.5–8.5 for successful fish farming in RAS. Very acidic pH impairs biological nitrification and causes carbon dioxide toxicity, while very basic pH may cause an increase in ammonia toxicity and reduce carbon dioxide stripping efficiency, apart from its direct effect on the aquatic animal. Biological nitrification continuously reduces the pH of water as this process consumes bicarbonate and generates H+ ions, thus necessitating the addition of base or alkalinity. The alkalinity of RAS water should be maintained at >100 mg/L for the proper functioning of the biological filter. As alkalinity is consumed in the process of nitrification, for every kg of feed fed, nearly 150–250 g of sodium bicarbonate must be applied, depending on the water exchange rate (HRT) and alkalinity of source water (Summerfelt et al. 2015; Timmons et al. 2018). Major sources of alkalinity supplementation are agriculture lime ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), sodium hydroxide (NaOH) and sodium carbonate ($NaCO_3$). Hardness is mainly due to the presence of Ca and Mg ions in water, and the recommended water hardness range is 50–300 mg/L for RAS. Hardness also decreases the toxicity of metals in water.

11.6 Components of RAS Culture System

11.6.1 Culture Tanks

Culture tanks are the vessels which hold the water where fishes are reared in RAS. They can account for 20–40% of the total capital cost of the system, depending on the material used. Many tank materials are available, such as plastic tanks, fibre-reinforced plastic (FRP), concrete, steel, HDPE and lined tanks supported either by GI mesh or wooden planks or tin sheets, depending on the local availability and the purpose. For example, plastic tanks can be used for nursery tanks, but for large tanks (>20 m^3), this may not be suitable. The most commonly used tank material is FRP, which can be shaped as per the requirement, constructed onsite or shipped in modules and assembled for large diameters.

The shape of the tank plays an important role in solid removal and providing uniform water quality for fish to grow. Circular tanks are mostly preferred for their excellent solid removal ability. They enable uniform water quality, and fishes distribute evenly when water inlets are appropriately designed. Further, circular tanks provide a continuum environment for fish swimming (see Fig. 11.3). Though raceways (rectangular tanks 2 m width and 15–50 m length) are widely used for farming rainbow trout in the flow-through system for space saving and easy operation, they have poor solid flushing ability, and regular manual brushing and cleaning are essential. A lot of water needs to be flushed during this process, and it also plumes the solids causing turbidity or fine solid load, which is not desirable when water needs to be recirculated. There is space wastage with circular tanks, which can be minimized through octagonal tanks that provide similar characteristics to that of

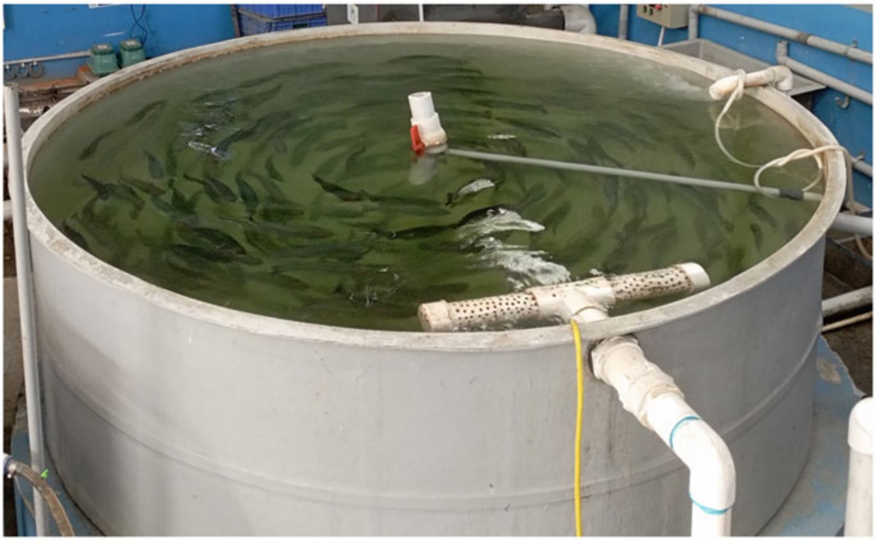

Fig. 11.3 FRP culture tank used at ICAR-DCFR, Bhimtal, for culture of rainbow trout in RAS

the circular tanks. One of the major advantages of circular tanks is that circular movement of water can be created by placing the inlet tangent to the tanks wall, and this causes the concentration and settling of solids at the centre bottom due to the teacup effect. Unlike the raceway system, this mechanism completely removes settleable solids without brushing or flushing. The diameter-to-depth ratio of 1:3–1:6 should be considered for proper distribution of fishes and easy operation and to enable visual observation of the health of the fishes and removal of dead fish (Timmons et al. 2018). There are several instances where fish farming has failed to operate in silo tanks (larger depth-to-diameter ratio). Contrarily, a higher diameter-to-depth ratio may be needed for certain fishes (e.g. flounder or shrimp), which do not distribute in the entire water column (Timmons et al. 2018).

Many outlet designs have been proposed to take advantage of the teacup effect of circular tanks, and at least two patents are available on the tank outlet design (particle trap, US Patent # 5636595, Lunde et al. 1997; and water treatment system, US Patent # 5593574, Van Toever 1997). In one of these designs, both the outlet systems are located at the centre. Most solids (up to 80% of settleable solids) are concentrated through a particle trap located at the bottom centre of the tank (through annular plates), drawing 5–10% water to a settling unit (swirl separators) located adjacent to the tank, while the remaining 90–95% of water is drawn out from elevated perforated screen plate. Cornell dual-drain outlet design also has two outlets, i.e. the central drain and side wall drain. Fifteen to twenty-five percent of water is drained through the central drain, which carries concentrated solids (Davidson and Summerfelt 2005; Timmons et al. 2018), and the side wall drain carries very less solids (TSS <2 mg/L) when compared to the central drain (~19 mg/L). Further, in Cornell dual-drain tanks, fish distribute uniformly and utilize the entire space available in the tank, enabling high stocking densities compared to other single- or double-drain tank outlet systems. Overall, dual-drain tanks have economic advantages as this reduces the required size of the microscreen drum filter, the number of backwash cycles, electricity cost and freshwater requirement. The mixed cell raceway is a new hybrid tank design incorporating raceway and circular tank characteristics by correctly positioning tank inlets and central outlets along the raceway bottom (Timmons et al. 2018).

11.6.2 Solid Removal Systems

Solids are generated from two primary sources, faecal matter and uneaten feed. Fish excretes almost 250–300 g of faecal matter for every kg of feed fed (dry matter basis), considering 70–75% dry matter digestibility. However, on a wet basis (75–80% moisture), this could be around 1–1.2 kg of faecal matter. The specific gravity and particle size distribution of the faecal matter are two major properties which decide which kind of solid removal system to be used. The above property also depends on the fish species reared, diet composition, faecal characteristics, water temperature and turbulence in the system. The three major principles for removing solids in water are gravity separation, filtration and floatation.

11.6.2.1 Settling Units

Early RAS models utilized inline large settling basins to separate and remove the solids before being recirculated. Settling basin is one of the cheapest ways to remove solids, as it does not require electricity and specific equipment (Timmons et al. 2018). However, due to labour requirements, poor solid removal efficiency and more space footprint (low hydraulic loading) as compared to other filtration methods, settling basins are mostly not used in modern RAS systems, and their use is primarily limited in effluent treatment systems of RAS.

When dual-drain culture tanks are used, settling tank dimensions can be reduced to a very small size (0.5–2 m diameter), as in the case of the Cornell dual-drain tank system where radial flow settlers (RFS) or swirl separators (SS) are used to settle the solids generated from 10–20% water drawn from the bottom drain (Davidson and Summerfelt 2005). Both SS and RFS are cylindrical-shaped tanks with conical bottom (Fig. 11.4). The major difference between them is the mode of entry of water into the settling tank. In the case of SS (also called as teacup settlers or hydro-cyclones), water enters tangentially to the tank surface, while in the case of RFS (also known as centre feed basins), the inlet water is injected centrally into the tank through a cylinder. Some studies suggest that RFS are more efficient in TSS removal as compared to swirl separators (TSS removal efficiency of 77 versus 37% in commercial salmonid RAS) (Davidson and Summerfelt 2005). In another model, the Aqua optima particle trap dual-drain tank utilizes very small swirl separators, as only 5% of water is drained from the bottom outlet, and it is claimed to collect nearly 80% of the settleable solid generated. In our study at ICAR-DCFR, Bhimtal, with a dual-drain tank, we observed that with an increase in hydraulic retention of

Fig. 11.4 Radial flow settler with radial entry of water (cylinder not shown) and swirl separator with tangent entry of water

10–15 min, the swirl separator collected 40–60% of the total solid generated. Further, we observed that the solid collecting ability of the swirl separator is also affected by the turbulence created by aeration in the culture tank and feed composition and size (Rajesh et al. unpublished data).

11.6.2.2 Microscreen Filter

Microscreen filter is the most widely and commonly used solid removal system in commercial RAS, as it provides automatic backwash function, with no head loss like in sand or bead filter and provides good TSS removal efficiency. There are at least three types of microscreen filters, namely, microscreen drum filter, belt filter and disc filter. Typically, a drum filter is used for RAS in-line removal of solids, while belt filters are mostly used for off-line dewatering of the solids before discharge and sometimes specifically used for typical solid waste of certain species (e.g. eel or to remove shrimp excavates) (Vinci et al. 2001).

Microscreen drum filter consists of stain steel mesh of varying micron size (30–70 μm), which is shaped as a cylinder or a drum with the help of cylindrical steel reinforcement or guide. The microscreen drum is connected to an electric motor with the help of gears to rotate the drum. Water passes through the microscreen drum filter and removes the TSS from water, and when the screen clogs, it prevents water from passing through, resulting in an increased water level. The water-level sensor in the drum filter then triggers the backwash mechanism where spray bars spray a jet of water onto the outer drum surface with simultaneous rotation of the drum screen, resulting in the cleaning of the trapped solids from the mesh (Fig. 11.5). The waste solids are collected in the tray provided below the top surface of the drum (as shown in Fig. 11.5) and are directed towards the effluent treatment facility.

The selection of a right-sized microscreen is very important since this has economic implications. A finer microscreen requires more repeated backwash, a large volume of backwash water and a larger drum filter, hence more operating costs than a larger microscreen. For example, when microscreen filter mesh size is

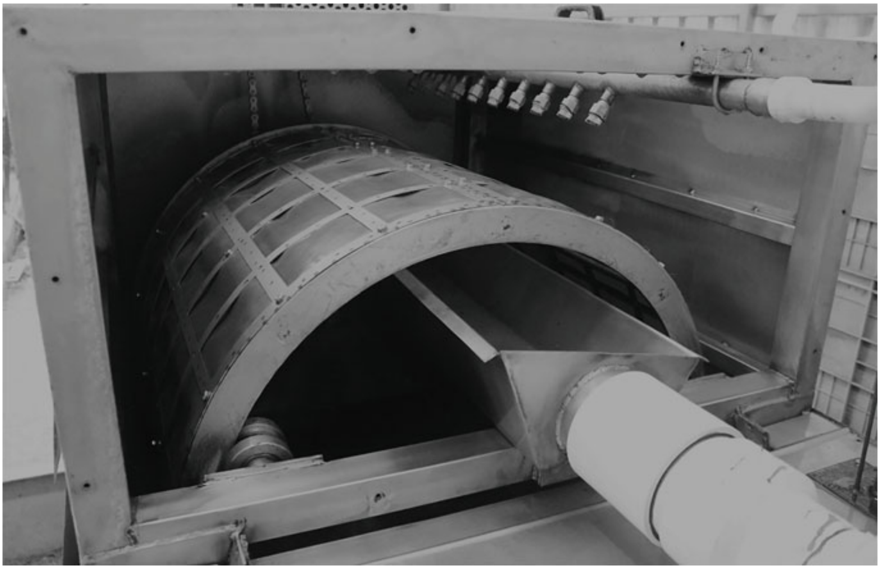

Fig. 11.5 Microscreen drum filter (screen size 50 μm) used in the cold-water RAS facility for rainbow trout production at ICAR-DCFR, Bhimtal

decreased from 100 to 30 μm, the amount of backwash water required increases from 50 to 200 L/kg feed with subsequent improvement in TSS capture efficiency from 21 to 90% (Mortensen 2000). Generally, the TSS capture efficiency of microscreen drum filter varies from 30 to 80%, and this depends on the inlet TSS level, i.e. the efficiency increases with an increase in inlet TSS level (Vinci et al. 2001).

Another commonly used solid removal system is granular filter media or sand filter or bead filters. These filters work as a solid removing system and as a biological filter. The use of swimming pool-type down-flow sand filter is not suitable for the RAS system because of the higher TSS load than the swimming pool and requires frequent backwash; thus, their use in RAS is discouraged. However, up-flow sand filters (fluidized sand filters) are used as biological filters, especially in cold-water RAS. The pressurized sand filter could be used for offline water polishing for specialized purposes like display aquariums or hatcheries. To overcome problems with the pressurized sand filter, bead filters were invented, where floating plastic beads (3–5 mm) were used in place of sand, and they work as both solid removal systems and biofilters (Malone and Beecher 2000). Bead filters require significantly less water and can be easily back washed through propeller-based or bubble injection. These bead filters are suitable for small-scale RAS and lightly loaded systems (special purposes like hatchery or brood stock maintenance). However, in large-scale commercial operations, granular filters are rarely used because of head loss caused by the bead or sand.

11.6.2.3 Foam Fractionators

Fine suspended and dissolved solids are one of the major issues in RAS, which increases as the culture of fish progress, decreasing the efficiency of all filtration devices (biofiltration, UV and ozone system). Foam fractionators remove fine and dissolved solids in water by injecting fine air bubbles; this precipitates the dissolved protein (other surfactants) on top of the bubble at the water surface. Foam is generated due to surfactant in water (protein and lipid), and if you see white foam on top of the water, it could be primarily due to decaying fish in the tank. Therefore, removing dead fish is very important; this requires good visibility through water (clear water) to see the dead fish at the bottom of the tank. The foam-precipitated particle size is mostly less than 30 μm, and foam fractionation is the most effective in salt water due to the formation of smaller bubble and higher surface tension of the seawater. The effectiveness of protein skimmer in freshwater is still a researchable issue, and studies have reported that foam fractionators removed only ~25% TSS in freshwater as compared to ~55% at 10 ppt salt water (Jafari et al. 2022). Nevertheless, another study found that foam fractionators along with ozone can work equally well in freshwater RAS in removing particulate matter and improving turbidity and UV transmittance (de Jesus Gregersen et al. 2021).

11.6.3 Biological Filter

In RAS, the ammonia excreted by fish needs to be removed (detoxified) before the water is recirculated to the culture tank, and this role is generally played by nitrifying bacteria grown on biofilter media (refer to Boxes 11.1 and 11.2). A biofilter's primary function is to provide a suitable surface area for the growth of nitrifying bacteria (biofilm; autotrophic bacteria like nitrifiers require some substrate to grow). Different types of biofilters such as rotating biological contactor (RBC), trickling filter, submerged gravel bed filter, moving bed bioreactor (MBBR), floating bead filter, fluidized sand filter, etc. are available to choose. Each type of biofilter has its advantage and disadvantage over the other. Its efficiency is calculated in terms of specific surface area (m^2 cross-sectional area/m^3 bio-media volume), hydraulic loading rate (m^3 water/m^2 biofilter cross-sectional area), volumetric nitrification rate (g TAN/day/m^3 of bio-media) and areal TAN conversion rate (g TAN/m^2 cross-sectional area per day) (Timmons et al. 2018). Here, we discuss only three types of biofilter which are commonly used in cold-water RAS.

Box 11.1

Box 1.
Biological filter utilizes the natural nitrifying microorganisms for detoxifying ammonia in water through a two step biological process.

Ex: Nitrosomonas

$2\,NH_4^+ + 3\,O_2 \rightarrow 2\,NO_2^- + 2\,H_2O + 4\,H^+$ (1)

Ex: Nitospira*, Nitrobacter

$2\,NO_2^- + O_2 \rightarrow 2\,NO_3^-$ (2)

* Nitrospira is a dominating nitrifier in the biological filter of a coldwater RAS.

Box 11.2

Box 2. **Overall nitrification**

$$NH_4^+ + 1.83\,O_2 + 1.97\,HCO_3 \longrightarrow 0.0244\,C_5H_7O_2N + 0.976\,NO_3^- + 2.9\,H_2O + 1.86\,CO_2$$

- A gram ammonia oxidation requires 4.18 g oxygen and 7.05 g alkalinity for biological nitrification.
- Therefore alkalinity of recirculating aquaculture water should be maintained > 100 mg/L $CaCO_3$ through the addition of alkalinity sources and dissolved oxygen in biological filter should be maintained > 2 mg/L.
- Thumb rule : every kg feed fed in the system requires 0.25 kg of $NaHCO_3$ to maintain desired alkalinity level in the recirculated water (Timmons et al., 2018).

11.6.3.1 Moving Bed Biological Reactor

Moving bed biological reactor (MBBR) is commonly used in treating municipal wastewater to remove nitrogen based on the above principle. MBBR consists of a reactor tank filled with specially designed bio-media (HDPE Kaldnes media K1–K5, the density of 0.96–0.98 g/cm^3) up to 30–65% of the reactor volume. These media are kept in the water column through the aeration process, and water from the fish tank (after treating for solid) is passed through the reactor (Fig. 11.6). The nitrifying bacteria grow over the surface of bio-media (internal and external surface) and convert ammonia to nitrate in a two-step process. These bio-media have a volumetric nitrification rate (VNR) of 500–1400 g TAN/day/m^3 and are suitable for high hydraulic loading rates. The major advantage of these MBBRs is that they are maintenance-free as media do not trap solids and hence do not require cleaning. The life span of these media is around 15 years.

11.6.3.2 Gravel Bed Biofilter

The gravel bed biofilter is the cheapest media as they are locally available, and the authors have personally observed that gravel-based biofilter matures faster than

A

B

Fig. 11.6 MBBR biofilter in RAS unit at ICAR-DCFR, Bhimtal (**a**), and fresh (right) and matured K5 media (left) used in MBBR (**b**)

MBBR (Akhtar et al. 2018). The gravel bed biofilter consists of a gravel bed of 15–20 cm depth, made up of 5–10 mm crushed and washed gravel, and a plumbing design (with 1 mm slits) laid below the gravel (which acts as an inlet for the filtered water). The pump draws water from the bottom of the gravel, which enables the water to pass through the gravel. The nitrifying bacteria grown over the gravel surface converts ammonia to nitrate (Fig. 11.7). The authors have observed that 10–15 mm gravel has a decent VNR of 300–400 g TAN/m^3/day at 20 °C. The gravel bed biofilter also filters fine solids, which is a blessing in disguise, but this necessitates a regular periodic cleaning, which is laborious. Therefore, gravel-based biofilter is not suitable for commercial setups and only advised for lightly loaded and small RAS units.

Fig. 11.7 Submerged gravel bed filtration used for hatchery RAS system at ICAR-DCFR, Bhimtal, India

11.6.3.3 Fluidized Sand Filter

Another type of commonly used biological filter is a fluidized sand filter. Sand (0.1–0.2 mm) offers a very high specific surface area and VNR of 0.2–0.4 kg TAN/day/m^3 of expanded bed (Summerfelt 2006). The fluidized sand filter consists of a large cylindrical tank of 3–5 m height. Water is injected at the bottom of the cylinder, and this expands the silica sand bed. The significant advantage of a fluidized sand filter is the scalability and smaller footprint. However, a fluidized sand filter requires regular maintenance as the sand becomes lighter over the period of operation due to the growth of bacteria and eventually flows into the culture tank. Sand also forms channels due to biofouling and electrostatic charge in the sand particle, necessitating regular sand replacement (Davidson et al. 2008; Summerfelt et al. 2001).

11.6.4 Degassing Unit: For Removal of Carbon Dioxide

Carbon dioxide in the system is generated due to fish and bacterial respiration, and it must be removed to maintain the carbon dioxide levels in the water below permissible safe limits (<20 mg/L). Generally, carbon dioxide is not an issue when aeration is used for supplying oxygen (~ stocking density of 40 kg/m^3), as aeration also strips out carbon dioxide. However, when standing biomass goes above 40 kg/m^3 and when pure oxygen is used for maintaining the oxygen level, carbon dioxide can reach a very high level. In this case, a separate carbon dioxide stripper or degasser is required. Carbon dioxide can be easily stripped out of the water when the water is exposed to air as the carbon dioxide level is very less in the air. Using this principle, water is passed through packing media in a stripping column, which increases contact time with atmospheric air via cross-ventilation (air blew from the opposite side with the help of a blower) of the water with air, with a water-to-air ratio (G/L) of 5:1–20:1 (Summerfelt et al. 2000, 2001; Timmons et al. 2018). The CO_2 stripper can be mounted on top of low-head oxygenators to avoid extra pumping costs (Summerfelt et al. 2000).

11.6.5 Aeration and Oxygenation

Oxygen is the major limiting factor in any RAS as there is a direct relationship between oxygen intake, feeding and growth. Aeration is a commonly used dissolved oxygen-enhancing method that mixes atmospheric air into the water through the help of an air pump and air diffuser. There are at least three kinds of aerators used in RAS: they are diaphragm blower, regenerative blower or ring blowers and root blower. The diaphragm blower is less noisy, consumes much less energy and is suitable only for small systems as blowers above 0.2 kW capacity are not produced (Fig. 11.8). Root blowers are used for large-scale RAS as any capacity blower can be manufactured. Pressurized air is supplied to the fish tank through the help of air stone or air-oxy tubes as fine bubbles. But, the aeration efficiency of this kind of aeration is only 3–7% and thus supports a maximum fish density of 40 kg/m^3 (Timmons et al. 2018). Another way to mix air in the water is through Venturi, and this method has better aeration efficiency and requires high-pressure pumping. Though paddle wheel aerators have higher oxygenation efficiency (up to 4 kg/O_2/KWh), their use is limited in closed tank systems (Boyd 1998). Another major drawback of aeration is that it creates turbulence in the culture tank water, breaking the faecal matter, causing turbidity and thereby reducing the solid removal efficiency of settling basins and drum filters.

Fig. 11.8 Different types of air blowers used for aeration in a RAS (from left, diaphragm, ring or regenerative and root blowers)

Pure oxygen is inevitable to grow fishes at stocking densities above 40 kg/m^3. Pure oxygen can be obtained from at least three sources, namely, high-pressure oxygen gas, liquid oxygen and onsite oxygen generators. The choice of source, however, depends on the local availability and cost. Besides, oxygen can be generated onsite through two types of generators, namely, pressure swing adsorption (PSA) and vacuum swing adsorption (VSA) oxygen generators; the latter is expensive and reliable compared to PSA. Both generators purify the atmospheric oxygen from air with the help of molecular sieves, which filter out nitrogen. Since oxygen is expensive, wastage of oxygen is not desirable, so oxygen mixing devices should achieve nearly 100% oxygen transfer efficiency. Therefore, unlike air, oxygen is not supplied through the diffusers; instead, they are provided through special devices such as Speece cone/oxygen cone, low-head oxygenator, packed column oxygenators and U-tube oxygenators (Summerfelt et al. 2000, 2001). The oxygen cone provides a very high oxygen transfer efficiency of 95–99%, with the oxygen level in the outlet reaching 60–90 mg/L when properly operated, but this requires high-pressure water flow. The low-head oxygenators can achieve 50–90% oxygen transfer efficiency at different gas-to-water ratios and are very easy to operate, and it also strips out nitrogen and carbon dioxide to a certain extent. The U-tube oxygen transfer device provides 30–50% oxygen transfer efficiency depending on the depth of the tube and can also be operated without power if sufficient water head is available (Timmons et al. 2018).

11.6.6 Disinfection System

To reduce heterotrophic and pathogenic bacterial load in the recirculated water, ultraviolet (UV) light and ozone filters are used. Besides disinfection, these filters also improve the water quality and clarity, as ozone oxidizes organic matter and nitrite and reduces the brownish (recalcitrant) colour of the water. Moreover, a UV filter is effective only in water with higher clarity. Therefore, ozone and UV filter work complementarily, as O_3 converts into O_2 when passed through UV, reducing the toxic effect of ozone on fish. Moreover, UV filter is placed after the ozonation in the RAS loop. For RAS purposes, open-type UV bulbs are suitable as quartz sleeves can be checked and cleaned for biofouling or calcium deposits. Ozone is generated onsite through an ozone generator and is mixed in water along with oxygen transfer devices such as an oxygen cone or LHO. The ozone has a half-life of <15 min, which also depends on the organic matter of the water. The suggested ozone dosage in RAS varies between 13 and 24 g ozone/day/kg feed. ORP meters can be used to control ozone dosing. In any case, the ozone level in the fish culture tank should not cross 300 mV; the dosage is accordingly controlled, as ozone is also toxic to fish. Further, the ozone can be destroyed by passing it through UV illumination. Ozone exposure to people working in the RAS system can be dangerous. Therefore, proper ventilation and precaution should be in place when ozone is used in the RAS fish farming system (Summerfelt et al. 2009).

11.6.7 Water Pumps

The water pump is the heart of the RAS, as it moves filtered and oxygenated water from filtration systems to fish and flushes the wastewater from the culture tank into the filtration system. Pumping cost can be a major operational expenditure, as it contributes to the total electrical cost, next only to heating and cooling systems. Therefore, the selection of pumps has economic implications. Different types of pumps are used in RAS, namely, centrifugal pumps (Fig 11.9), axial pumps, airlift pumps, etc. Centrifugal pumps are designed to pump water to a very high head (> 30 m) and are often used in RAS, particularly when oxygen cones are used for oxygenation. The axial pumps are suitable for lower-head purposes (4–9 m) and are very useful in RAS when appropriately designed. The axial pump can pump large volumes of water at lower heads and consumes much less electricity than a centrifugal pump. However, axial pumps are not generally available for a small flow rate. Airlift pumps are suitable for lifting the water to a maximum of 15 cm head, and it does not contain any moving part; water is lifted with the help of an aeration manifold or diffusers. Though airlifts are cheaper and have very low operating costs, they are only useful in small systems and are not used in commercial RAS setups (Timmons et al. 2018). For the selection of an appropriate pump, the water flow requirement is calculated from the mass balance estimation, depending on the production target in the tank and the oxygen source used. The time required to exchange one tank volume of water is called hydraulic retention time (HRT) of the tank. For farming rainbow trout in RAS, generally, less than 30 min of HRT is

Fig. 11.9 Multiple centrifugal pumps used in RAS facility at ICAR-DCFR, Bhimtal

essential (standing biomass >40 kg/m^3) to supply sufficient oxygen and for flushing waste (TSS, CO_2, TAN) (Fig. 11.9).

11.6.8 Heating and Cooling System

Depending on the species and the local climatic conditions, heating and cooling systems may be required to maintain controlled temperature conditions in RAS. Heating can be done with the help of electric heaters (titanium heating elements), heat pumps or gas heaters. In terms of operating costs, heat pumps can cost-effectively heat the water, but they are expensive. Cooling of water can be done with the help of industrial chillers. Heating and cooling costs could account for most of the total electrical cost in RAS; therefore, heating and cooling requirements need to be ascertained with the economic benefits it provides. Utilizing geothermal energy is another potential option to maintain the required water temperature in the system.

11.6.9 Monitoring Equipment, Emergency Systems and Backups

One of the major challenges of intensive aquaculture (e.g. RAS) is the requirement for 24×7 monitoring of the system. Since fishes are reared at high density (up to 120 kg/m^3) in RAS, any component failure (pump, oxygen supply) or power cut even for 15 min could end up in a mass fish loss if the issue is not addressed immediately. Therefore, continuous system monitoring (Fig. 11.10) is crucial, and backups are essential. Backups for the pump, aeration, oxygen supply and an electricity generator are mandatory for RAS operation. Out of our own experience,

Fig. 11.10 Real-time DO monitor and alarming system (YSI 55000D) used at ICAR-DCFR, RAS facility at Bhimtal

we advise that it is better not to do RAS-based fish farming without adequate backups and risk avoidance measures. Dissolved oxygen is one crucial factor that can kill fishes in minutes when they are below the threshold level. In intensive rearing conditions, oxygen levels can quickly drop when pumping, oxygenation system or power failure occurs. Therefore, dissolved oxygen monitoring 24×7 is the first point of critical control. There are suppliers who provide real-time dissolved oxygen monitoring and control systems that can be connected to oxygenation devices and an alarming system that triggers an alarm when DO drops below a set threshold level. However, reliable and durable DO sensors are expensive and may be required for all rearing tanks. Another way to monitor water flow or the water level is through a water flow meter or water-level sensors which are cheaper and also reliable, but it is not a replacement for DO measurements. DO measurements and ozone levels (ORP) should be checked several (at least three to four) times a day. At the same time, other water quality parameters, such as ammonia, nitrite, nitrate, carbon dioxide, alkalinity, pH and TSS need to be checked regularly to ensure that all the RAS equipment is functioning to the expected operational efficiency. There could be many practical problems during the culture operation, if the system is not appropriately designed. For example, mortality of a few fishes (may be due to any reason) and failure to remove the dead fish can cause blockage in the central drain outlet, causing water to overflow, and the following day you might end up seeing all fish on the floor. Therefore, proper system design (e.g. dual drain, proper outlet) and system monitoring are extremely critical and essential.

11.7 Growing Fish in RAS

In RAS, fish should be grown near the system's carrying capacity at all times, to take maximum benefit of system design. Therefore, proper bio-planning is required while designing and operating the system. In the case of rainbow trout farming, fishes should be grown in different phases at least in four culture tanks, namely, hatchery system, nursery1, pre-grow-out and grow-out. This multiple tank rearing system is useful to reduce operational costs and save space. Moreover, this allows the farmer to harvest fish multiple times and regularly supply fish as per the market demand. It is always good to start from eyed ova, as it is easy to transport and also for biosecurity measures (eggs can be disinfected with povidone-iodine solution). Fish are then moved through the different tanks designated for the rearing phase (nursery and grow-out) during culture. This way, a new batch of eggs is brought as per the bio-plan, and fish are sold from grow-out tanks as per the market demand instead of dumping fish in the market all at once.

11.8 Feed and Feeding

Feed and feeding are one of the most critical factors (technically and economically) that determine the success of RAS operation, as it is integral to the equilibrium between fish growth, health and water quality maintenance. Advanced aquaculture systems such as the RAS require an equally advanced feed specific to the cultured species. Though the basic nutritional requirements for fish in RAS remain the same, due focus must be given to feed conversion efficiency into fish biomass as well as the efficiency of solid and dissolved waste removal. To improve the water filtration efficiency in RAS, research is being done on optimizing feed quality (physical and nutritional) and feeding strategies to improve feed palatability, digestibility, functionality and efficiency, as well as faecal stability and nutritional waste removal. In short, feeds for fish grown in RAS should be complete in nutrition, should elicit superior biological performance and must yield the desired faecal characteristics (high decantation rates) to maintain good water quality. The physical characteristics of faeces, such as dry matter, particle size distribution, viscosity, stability/disintegration and settling properties are quantified to aid the designing of filtration and waste removal systems in RAS (Tillner 2019). On the other hand, the quality of faeces and its recovery is decided by factors such as dietary ingredients, processing and the inclusion of additives. Some commercial feeds specifically designed for RAS production systems are already available in the global market. This includes Skretting's next-generation RCX feeds with high structural integrity for salmon production in RAS, BioMar's LARVIVA ORBIT feed concept to improve the efficiency of marine nurseries and Aller Aqua's PowerRAS concept to match RAS sophistication. In India, RAS-specific feeds are presently under research investigations and are not available commercially. Feeding management is another vital aspect of RAS, and continuous feeding throughout the day (every 2 h through auto feeders) is the main strategy to get faster fish growth. This also helps in the uniform excretion of ammonia (throughout the day) and does not put a sudden load on the biological filter due to a spike in ammonia or nitrite levels. The following feeding chart (Fig. 11.11) explains the feeding rate and feed amount in relation to fish size and

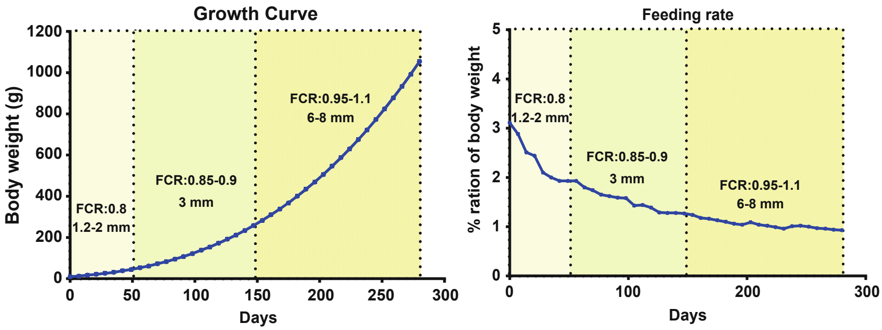

Fig. 11.11 Relation between feeding rate and growth rate of rainbow trout

growth rate. Feeding should be stopped whenever there is an issue with oxygen and water quality until the problems is resolved.

11.9 Depuration

Incidences of off-flavour or off-taste (muddy/musty odour) have often been reported in RAS-produced fish. The chemical compounds responsible for this muddy odour are geosmin and 2-methylisoborneol (MIB), which are produced as secondary metabolites by various microorganisms (Azaria and van Rijn 2018). Due to their hydrophobic nature, these compounds accumulate in the fish flesh (lipids) through simple diffusion (against the concentration gradient). The human nose can detect geosmin and MIB concentrations of less than 0.05 μg/L (50 parts per trillion) in the fish flesh, and thus off-flavour tainted fish flesh often causes consumer complaints and rejection. The accumulation of off-flavour compounds is prevalent mainly in RAS with low water exchange rates (Davidson et al. 2014).

Depuration or purging is a common method to reduce off-flavour in fish grown in RAS. Depuration involves rearing fish in a freshly disinfected tank, without any feeding for 7–12 days, with a slow exchange of freshwater (HRT of <1 day). This purging can be quickened with the addition of peracetic acid or hydrogen peroxide and ozone and UV filtration (Davidson et al. 2014; Lindholm-Lehto et al. 2022). During this process, the off-flavour compounds are passively depurated from the fish flesh into the water, which is later oxidized by ozone or flushed with freshwater. Recently, a novel advanced oxidation process (AOP) has also been developed to remove off-flavour through a multi-component action mechanism which can remove off-flavour in Atlantic salmon within 6 days, as compared to more than 10 days in other depuration methods (Kropp et al. 2022).

11.10 Waste Management

RAS generates concentrated effluents (i.e., solids, mostly from drum filter backwash and settling unit discharge) and nitrate-rich water, which need to be treated before releasing them into natural water bodies. One of the common effluent treatment methods is to discharge the effluent into a settling basin, followed by artificial wetlands, which eventually reduce nitrate and phosphorous levels in discharge (Martins et al. 2010). If the RAS is located near an agriculture field, the effluents can be directly used as fertilizer in the form of dilute slurry. Another way to remove sludge from the effluent is through sludge thickening using a belt filter, with or without flocculation. Geotextile bags can also be used to dewater the aquaculture solid waste, and dewatered solids could be used as organic fertilizer for agriculture (Guerdat et al. 2013). The use of RAS sludge for biogas is an exciting option, but unfortunately, biogas production is not efficient as that of cow dung due to effluent composition (minerals, protein and fibre). Therefore, currently, RAS sludge can only be used as a co-digestion mixture with ruminant manure, and further research are underway to improve the biogas production efficiency from aquaculture waste (Mirzoyan et al. 2010; Choudhury and Lepine 2020). Nitrate levels in the effluent water can be reduced through denitrification or by connecting it to de-looped hydroponics for integrated agricultural production and higher economic benefits.

11.11 Status of RAS in India

In India, RAS-based food fish production is still in its infancy, and the major bottlenecks are technical know-how and high initial investment. Commercial rainbow trout farming in RAS could be a reality soon, as rainbow trout is considered a premium high-value fish. In this direction, the ICAR-Directorate of Coldwater Fisheries Research has been working for the past 4 years. To overcome the challenges associated with conventional trout production systems, we have designed, established and successfully validated the feasibility of intensively farming rainbow trout in a pilot-scale cold-water RAS facility at Bhimtal, Uttarakhand. The production capacity of this pilot-scale RAS is nearly 2 tonnes per year and is mainly used for research, demonstration and training. Concurrently, ICAR-DCFR has also designed, developed and validated hatchery and nursery RAS systems for incubating trout eggs and rearing trout fry in multiple locations. Hatchery RAS under controlled conditions for rainbow trout could be a catalyst for increasing the production and productivity in remote high-altitude locations like Ladakh in India. Despite the extreme weather conditions in Ladakh, we have tested and validated that egg incubation and fingerling production can be successfully achieved in a shorter period under controlled RAS conditions. This allows sufficient time for fish to grow in the outdoor flow-through system when the water temperature is in a suitable range during summer (April–October), thus reducing the overall crop duration. Currently, only two commercial RAS-based rainbow trout farming facilities have been established or planned in India, namely, one at Awantipora, Kashmir, with a system volume of 500 m^3 (production capacity of 15 tonnes, operational from 2021) and another at Hyderabad, Telangana (initiated and expansion proposed), with a projected production capacity of 300 tonnes.

11.12 Challenges

The primary reasons for the slow adaption of RAS technology are high initial investment and a long payback period compared to other aquaculture systems (Martins et al. 2010; Badiola et al. 2012). RAS requires backups like emergency oxygenation, electricity generator, vital equipment and building, which increases the initial cost. Further, the production cost of fish in RAS is higher than in conventional aquaculture systems, but the same product from both systems has to compete for the same price in the open market (Ahmed and Turchini 2021). Another major challenge is the high energy requirement in RAS. Generally, energy requirement could vary from 5 to 20 kWh for every kg of fish produced in RAS depending on species, location and system design. With the addition of temperature control (heating and cooling), energy requirements can increase further (Martins et al. 2010; Badiola et al. 2017, 2018).

Other major causes for the failure of RAS are inadequate initial planning, poor system design, operational shortcomings and lack of technical expertise. Across the globe, losses in many commercial RAS facilities have been attributed to an initial poor design, wrong design calculations, use of inferior or cheap materials for RAS construction to cut down cost, improper management (lack of training), poor or wrong equipment selections and lack of proactive response to sudden equipment failures or water quality issues (Badiola et al. 2012). It is also reported that 50% of globally surveyed RAS-based aquaculture firms had rebuilt or redesigned their RAS due to failure resulting from the poor or inadequate initial design. Therefore, it is crucial to choose the right consultant or firm to design, construct and operate RAS. One must ensure that the firm has good prior experience in designing and building RAS facilities for the targeted species with a proven track record of successful fish production.

Current RAS treatment systems mainly address ammonia, nitrite, nitrate, carbon dioxide, alkalinity, pH and oxygen levels in the water. However, the removal of minerals, drug residues and metabolites is still poorly known or understood, and these may accumulate in the system causing chronic health issues and eventually affecting the quality and safety of the fish (Davidson et al. 2009; Martins et al. 2010). Some early studies have indicated that the chronic accumulation of metabolites and metals could cause deformities and abnormal swimming behaviour in rainbow trout reared in low exchange RAS (Davidson et al. 2011). Off-flavour in RAS-reared fish is another major issue affecting consumer acceptability, market price and farm economics due to additional depuration required in current RAS designs (Davidson et al. 2014; Badiola et al. 2012). Most of the publicly available knowledge on RAS is either from experimental scale units or semi-commercial operations carried out by research institutes. Knowledge gained on commercial RAS operations and management is closely safeguarded by private industries and is not publicly available due to business interests. Further, the firm seldom reports detailed information on the cause of failures due to fear of negative publicity and consumer scrutiny (Badiola et al. 2012).

11.13 Opportunities and Way Forward

Despite the above challenges, fish production from RAS has steadily increased in EU countries in the last 10 years (29,513 tonnes in 2018, Eurostat). In Asian countries, RAS is being slowly adopted due to rising land prices and competitive limitations of water resources (Ahmed and Turchini 2021). In India, RAS technology is promoted through various government schemes and initiatives, catering to different operational scales from small (mini) to entrepreneurial pilot systems. The driving force for adopting of RAS technology could be increasing consumer awareness of fresh, safe and sustainable fish and seafood. Since RAS can be located near the market, fresh and locally produced seafood can be supplied to consumers. The environmental advantage of RAS could be another driver, as RAS is considered as a climate-smart aquaculture practice (EUMOFA 2020). Another significant opportunity that RAS provides is the controlled and secure conditions for intensive farming, which allows the culture of high-value niche market species or exotic species (Atlantic salmon, rainbow trout, seabass and shrimps) near the market, which are otherwise not possible using conventional aquaculture practices.

Globally, the energy requirement and associated costs incurred are being reduced through RAS design optimization, utilizing low-head pumps, improving biofilter performance and utilization of renewable energy resources. Heating and cooling costs can be reduced by using geothermal energy, solar energy or other renewable sources and waste heat from other industries (Badiola et al. 2012). For example, low-temperature effluent water from a fish processing industry could be used for cooling purposes in RAS (in chiller condensers) to grow cold-water species in tropical areas. Likewise, waste heat generated from diesel generators or other industries can be used for heating purposes in RAS during winter. Furthermore, the development of simple and small-scale RAS with reduced investment can be a game-changer for quicker/wider adaptation of RAS for backyard fish production in rural and semi-urban areas of developing countries (Ahmed and Turchini 2021). New biofiltration methods such as the anaerobic ammonia-oxidizing (anammox) technology, which converts TAN directly into nitrogen gas, could be a significant step to make RAS more environment-friendly while reducing the operational cost (with lower energy usage, alkalinity requirement, oxygen requirement and depuration requirement) (Martins et al. 2010).

Additionally, inducing controlled anaerobic conditions within the RAS loop could be a possible solution to ameliorate the off-flavour issue in fish flesh (Guttman and van Rijn 2008). Using effluents as fertilizer or co-digestion mixture for biogas production, RAS technology can become a net energy producer than a consumer. This biogas, in turn, can be used for heating or as fuel for electricity generation. Integration with other agricultural practices such as aquaponics and algae production (macrophytes/aquatic weeds) could improve the water quality, reduce greenhouse gas emissions and generate additional products with economic benefits (Martins et al. 2010; Badiola et al. 2012). Future research should also aim to develop hybrid technologies such as RAS with bio-floc technology (BFT) to overcome the disadvantages of one system with the advantages of the other (Kuhn et al. 2009).

References

Ahmed N, Turchini GM (2021) Recirculating aquaculture systems (RAS): environmental solution and climate change adaptation. J Clean Prod 297:126604

Akhtar MS, Rajesh M, Ciji A, Sharma P, Kamalam BS, Patiyal RS, Singh AK, Sarma D (2018) Photo-thermal manipulations induce captive maturation and spawning in endangered golden mahseer (Tor putitora): a silver-lining in the strangled conservation efforts of decades. Aquaculture 497:336–347

Azaria S, van Rijn J (2018) Off-flavor compounds in recirculating aquaculture systems (RAS): production and removal processes. Aquacult Eng 83:57–64
Badiola M, Mendiola D, Bostock J (2012) Recirculating aquaculture systems (RAS) analysis: main issues on management and future challenges. Aquacult Eng 51:26–35
Badiola M, Basurko OC, Gabiña G, Mendiola D (2017) Integration of energy audits in the life cycle assessment methodology to improve the environmental performance assessment of recirculating aquaculture systems. J Clean Prod 157:155–166
Badiola M, Basurko OC, Piedrahita R, Hundley P, Mendiola D (2018) Energy use in recirculating aquaculture systems (RAS): a review. Aquacult Eng 81:57–70
Boyd CE (1998) Pond water aeration systems. Aquacult Eng 18(1):9–40
Bregnballe J (2015) A guide to recirculation aquaculture: an introduction to the new environmentally friendly and highly productive closed fish farming systems. Food and Agriculture Organization of the United Nations (FAO) and EUROFISH International organization, Canada, pp 1–93
Cho CY, Bureau DP (1998) Development of bioenergetic models and the fish-PrFEQ software to estimate production, feeding ration and waste output in aquaculture. Aquat Living Resour 11(4): 199–210
Choudhury A, Lepine C (2020) Exploring anaerobic digestion for waste management in RAS, Hatchery International. https://www.hatcheryinternational.com/exploring-anaerobic-digestion-for-waste-management-in-ras/. Accessed 29 Jun 2022
Colt J, Watten B, Pfeiffer T (2012) Carbon dioxide stripping in aquaculture–part II: development of gas transfer models. Aquacult Eng 47:38–46
Couturier M, Trofimencoff T, Buil JU, Conroy J (2009) Solids removal at a recirculating salmon-smolt farm. Aquacult Eng 41(2):71–77
Davidson J, Summerfelt ST (2005) Solids removal from a coldwater recirculating system—comparison of a swirl separator and a radial-flow settler. Aquacult Eng 33(1):47–61
Davidson J, Helwig N, Summerfelt ST (2008) Fluidized sand biofilters used to remove ammonia, biochemical oxygen demand, total coliform bacteria, and suspended solids from an intensive aquaculture effluent. Aquacult Eng 39(1):6–15
Davidson J, Good C, Welsh C, Brazil B, Summerfelt S (2009) Heavy metal and waste metabolite accumulation and their potential effect on rainbow trout performance in a replicated water reuse system operated at low or high system flushing rates. Aquacult Eng 41(2):136–145
Davidson J, Good C, Welsh C, Summerfelt ST (2011) Abnormal swimming behavior and increased deformities in rainbow trout Oncorhynchus mykiss cultured in low exchange water recirculating aquaculture systems. Aquacult Eng 45(3):109–117
Davidson J, Schrader K, Ruan E, Swift B, Aalhus J, Juarez M, Wolters W, Burr G, Good C, Summerfelt ST (2014) Evaluation of depuration procedures to mitigate the off-flavor compounds geosmin and 2-methylisoborneol from Atlantic salmon Salmo salar raised to market-size in recirculating aquaculture systems. Aquacult Eng 61:27–34
de Jesus Gregersen KJ, Pedersen LF, Pedersen PB, Syropoulou E, Dalsgaard J (2021) Foam fractionation and ozonation in freshwater recirculation aquaculture systems. Aquacult Eng 95: 102195
Espinal CA, Matulić D (2019) Recirculating aquaculture technologies. In: Goddek S, Joyce A, Kotzen B, Burnell GM (eds) Aquaponics food production system. Springer, Cham, pp 35–76
European Market Observatory for Fisheries and Aquaculture products (EUMOFA) (2020) Recirculating aquaculture systems. Publications Office of the European Union, Luxembourg, pp 1–44
EUROSTAT (2018) Aquaculture production for human consumption (fish_aq2a). https://www.eumofa.eu/en/web/eumofa/sources-of-data. Accessed 29 Jul 2022
FAO (2020) The State of World Fisheries and Aquaculture. Sustainability in action. Food and Agriculture Organization of the United Nations, Rome. https://doi.org/10.4060/ca9229en
Guerdat TC, Losordo TM, DeLong DP, Jones RD (2013) An evaluation of solid waste capture from recirculating aquaculture systems using a geotextile bag system with a flocculant-aid. Aquacult Eng 54:1–8

Guttman L, van Rijn J (2008) Identification of conditions underlying production of geosmin and 2-methylisoborneol in a recirculating system. Aquaculture 279:85–91

Ip AY, Chew SF (2010) Ammonia production, excretion, toxicity, and defense in fish: a review. Front Physiol 1:134

Jafari L, de Jesus Gregersen KJ, Vadstein O, Pedersen L-F (2022) Removal of microparticles and bacterial inactivation in freshwater RAS by use of foam fractionation, H2O2 and NaCl. Aquacult Res 53:3274–3282. https://doi.org/10.1111/are.1580

Kropp R, Summerfelt ST, Woolever K, Johnson SA, Kapsos DW, Haughey C, Barry TP (2022) A novel advanced oxidation process (AOP) that rapidly removes geosmin and 2-methylisoborneol (MIB) from water and significantly reduces depuration times in Atlantic Salmon Salmo salar RAS aquaculture. Aquacult Eng 97:102240

Kuhn DD, Boardman GD, Lawrence AL, Marsh L, Flick GJ (2009) Microbial floc meal as a replacement ingredient for fish meal and soybean protein in shrimp feed. Aquaculture 296:51–57

Lindholm-Lehto PC, Kiuru T, Hannelin P (2022) Control of off-flavor compounds in a full-scale recirculating aquaculture system rearing rainbow trout Oncorhynchus mykiss. J Appl Aquac 34(2):469–488

Lloyd R, Jordan DHM (1964) Some factors effecting the resistance of rainbow trout (*Salmo giardnerii* Richardson) to acid waters. Int J Air Water Pollut 8:393–403

Lunde et al (1997) Particle trap, US patent # 5636595. Accessed 10 Oct 1997

Malone RF, Beecher LE (2000) Use of floating bead filters to recondition recirculating waters in warmwater aquaculture production systems. Aquacult Eng 22(1–2):57–73

Martins CIM, Eding EH, Verdegem MC, Heinsbroek LT, Schneider O, Blancheton JP, d'Orbcastel ER, Verreth JAJ (2010) New developments in recirculating aquaculture systems in Europe: a perspective on environmental sustainability. Aquacult Eng 43(3):83–93

Mirzoyan N, Tal Y, Gross A (2010) Anaerobic digestion of sludge from intensive recirculating aquaculture systems. Aquaculture 306(1–4):1–6

Molony B (2001) Environmental requirements and tolerances of rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) with special reference to Western Australia: a review, vol 130. Department of Fisheries, Government of Western Australia, Perth, WA, pp 1–32

Mortensen H (2000) Drum filter efficiency as particle separator in a recirculated system. Global Seafood Alliance. https://www.globalseafood.org/advocate/drum-filter-efficiency-as-particle-separator-in-a-recirculated-system/

Naylor RL, Hardy RW, Buschmann AH, Bush SR, Cao L, Klinger DH, Little DC, Lubchenco J, Shumway SE, Troell M (2021) A 20-year retrospective review of global aquaculture. Nature 591(7851):551–563

Summerfelt ST (2006) Design and management of conventional fluidized-sand biofilters. Aquacult Eng 34(3):275–302

Summerfelt ST, Vinci BJ, Piedrahita RH (2000) Oxygenation and carbon dioxide control in water reuse systems. Aquacult Eng 22(1–2):87–108

Summerfelt ST, Bebak-Williams J, Tsukuda SCOTT (2001) Controlled systems: water reuse and recirculation. In: Wedermeyer G (ed) Second edition of fish hatchery management. American Fisheries Society, Bethesda, MD, pp 285–295

Summerfelt ST, Sharrer MJ, Tsukuda SM, Gearheart M (2009) Process requirements for achieving full-flow disinfection of recirculating water using ozonation and UV irradiation. Aquacult Eng 40(1):17–27

Summerfelt ST, Zühlke A, Kolarevic J, Reiten BKM, Selset R, Gutierrez X, Terjesen BF (2015) Effects of alkalinity on ammonia removal, carbon dioxide stripping, and system pH in semi-commercial scale water recirculating aquaculture systems operated with moving bed bioreactors. Aquacult Eng 65:46–54

Tillner R (2019) Sophisticated feeds for RAS. International Aqua Feed. https://aquafeed.co.uk/sophisticated-feeds-for-ras-20780

Timmons MB, Guerdat T, Vinci BJ (2018) Recirculating aquaculture, 4th edn. Ithaca Publishing Company LLC©, Ithaca, NY

Van Toever (1997) Water treatment system, US patent # 5593574. Accessed 14 Jan 1997

Vinci B, Summerfelt S, Bergheim A (2001) Solids control. In: Summerfelt ST (ed) Presentation Notebook: Aquacultural Engineering Society Workshop: Intensive Fin-fish Systems and Technologies. Aquaculture 2001. International Triannual Conference and Exposition of the World Aquaculture Society, January 23, Disney's Coronado Springs Resort, Orlando, FL, pp 1–73