Review Article

A REVIEW ON RECIRCULATING AQUACULTURE SYSTEMS: CHALLENGES AND OPPORTUNITIES FOR SUSTAINABLE AQUACULTURE

Nilav Aich[1], Suman Nama[2], Abhilipsa Biswal[2] and Tapas Paul[2*]
[1]*Department of Fisheries, Government of Tripura, Tripura, INDIA*
[2]*ICAR-Central Institute of Fisheries Education, Mumbai-400061, INDIA*
*Corresponding author's E-mail: tapaspaul0511@gmail.com

KEYWORDS:

Biosecurity, Denitrification reactors, Recirculatory aquaculture system, Wetlands

ARTICLE INFO

Received on: 12.10.2019
Revised on: 19.02.2020
Accepted on: 27.02.2020

ABSTRACT

Aquaculture is one of the fastest growing industry and grows at a pace of 1.1% rate per year. In recent times, current global climatic condition does not allow horizontal expansion of this industry anymore. To further increase the aquaculture production, requirement of a robust technology is evident. Recirculatory Aquaculture System (RAS) allows increasing the fish production by many folds using limited resources. Water conservation, biosecurity and high production are key features of this technology. The major challenges seem to be affecting this industry includes poor management, lack of knowledge about the technology, high investment and occurrence of diseases and pathogens. Several researches are being carried out to improve technical aspect in recirculating loop, efficient use of system by-products and finding an alternative source of energy. Recent advancement in RAS such as denitrification reactors, sludge thickening technologies and ozone treatments results in minimal use of water, waste discharge and energy use. With greater knowledge about the system and understanding the interaction between its components, this technology has the potential to bring revolution in aquaculture sector.

INTRODUCTION

Being the fastest growing food-producing sector aquaculture production has increased dramatically over the past five decades reaching 80.0 million tonnes of food fish harvested (FAO, 2018). It is predicted that by 2030 an additional 40 million tonnes of aquatic food will be needed to maintain the current per capita consumption. In order to produce more food from the same area of land while reducing the environmental impacts requires more sustainable intensification methods for feeding 9 billion people. (Godfray *et al.,* 2010). The ability to maintain optimal and constant water quality conditions throughout the culture period lead to gain more attention for aquafarmers. In this context Recirculatory Aquaculture System (RAS), which requires limited resource for greater production and provides environment sustainability gain significant importance. RAS is used for fish production in indoor tank-based systems where water exchange is limited and the use of biofiltration is required to reduce ionized and unionized ammonia level (Timmons *et al.,* 2010). RAS are designed in such a way that minimise water consumption, control culture conditions and allow waste streams to be fully managed. They can also provide some degree of biosecurity through measures to isolate the stock from the external environment. This system filters the water through a series of biological and mechanical filtration systems and makes it clean for recycling back through fish culture tanks and more than 90% of the water is re-circulated through the culture units (Sugita *et al.*, 2005). In contrast with the conventional method of growing fish outdoors unit, this system rears fish at very high densities in indoor tanks with a "controlled" environment. The major pre-requisite for RAS is clean water, dissolved oxygen, and optimal temperatures for ensuring proper growth and environment sustainability. Keeping in view of all these, the present review aims to highlight the advantages, challenges and future opportunities of RAS.

Design of RAS

The basic principle behind the RAS is to re-circulate the water through flow-through fish farm by diverting the water supply through ponds or tanks. However, recirculation implies treatment of some or all of the discharge water and returning this to the fish rearing system. In RAS, a key design parameter is the ratio of recycled water to waste water (i.e. percentage of recycled water in the fish tank inflow water). The main functional parts of a RAS include: 1. growing tank, 2. sump of particulate removal device, 3. biofilter, 4. oxygen injection with U-tube aeration and 5. Water circulation pump (Fig. 1). Depending on the type of fish species to be cultured, a thermostat system required to be installed for optimum maintenance of water temperature. In order to reduce organic and bacteria loads, ozone and UV sterilization are used.

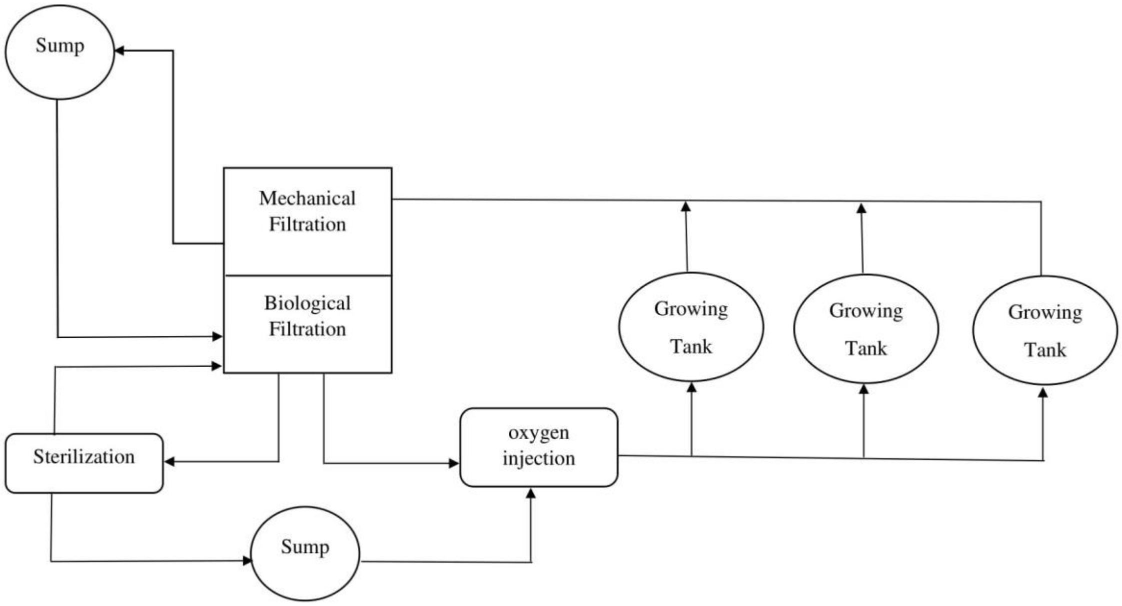


Figure 1: Schematic diagram of a modern RAS

Advantages of RAS

The major advantage of RAS is that it can reduce direct operational costs of feed, predator control and parasites and potentially eliminate release of parasites to recipient waters. Moreover, RAS reduce dependency on antibiotics and therapeutants generate marketing advantage of high quality 'safe' seafood. RAS production can promote versatility in terms of location for farming, proximity to market and construction on brown-field sites. However, they still need to be in close proximity to source water supplies and consideration needs to be given to local water quality and aesthetics since RAS farms resemble industrial buildings. RAS system involves culture of a broad range of species irrespective of temperature requirements and also enable secure production of non-endemic species (Martins *et al.*, 2010). Optimum environmental conditions promote excellent FCRs with some high value marine species achieving market size in 50% of time taken in sea cages. Due to highly intensive control, RAS provide a suitable culture condition of fish in terms of water flow, stocking density and maintain optimum physiological balance of fish. RAS facilitate to remove metabolic wastes from the fish (notably faeces, ammonia and carbon dioxide), remove waste feed and breakdown products (solid and dissolved organic compounds) and maintain temperature and water chemistry parameters within acceptable limits (Murray *et al.*, 2014).

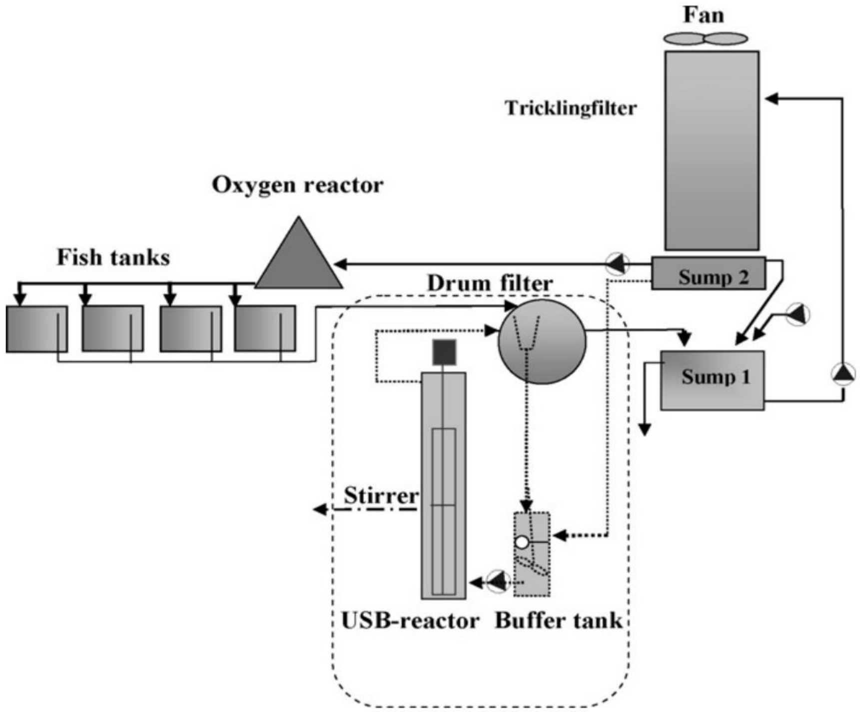
Challenges for RAS technology

Lack of well experienced technically sound expertise of RAS culture is one of the major concerns for sustainable aquaculture production. Former cage or hatchery managers are not necessarily having sufficient knowledge to operate commercial scale RAS considering the water quality variables that require 24h in line monitoring. The economic viability of a RAS project is often based on assumptions and variables related to expected market price, utilization of the waste stream, product quality, optimal and maximum densities achievable, energy costs and costs relating to depreciation and interest on loans (Martins *et al.*, 2010). Maintaining optimum water temperatures for species like sea bass or bream, as opposed to species like turbot or halibut, is likely to be less energy demanding in the UK provided the farm buildings are properly insulated (Moestrup *et al.*, 2014). Experienced technicians to work with these species will need to be recruited from abroad. Species selection for RAS production is a critical issue. Production of a commodity species in RAS which has to compete with the same product either imported or farmed using a lower production cost method requires serious risk assessment. It is feasible to reduce the operational cost of RAS through utilisation of farm waste for value added products. The utilisation of RAS farm waste for on-site energy production is also feasible and the potential contribution in trial studies indicates this approach could be useful (Mirzoyan *et al.,* 2010). However, such type of value-added production from RAS is still in nascent stage.

Biosecurity and disease occurrence in RAS system

Biosecurity implies any company policy and procedures used on a farm that reduce the risk of pathogen introduction or spread through the facility if they are introduced. One of the primary advantages of RAS technology is that it provides the farmer with the opportunity to reduce disease outbreaks and actually eliminate some diseases altogether (Blancheton, 2000). However, while RAS can create optimum conditions for fish culture, inferior designs may inadvertently provide favourable conditions for disease outbreaks or the reproduction of opportunistic pathogens (Delabbio *et al.,* 2004; Timmons *et al.,* 2010). Once the pathogens have entered to the RAS, their potential impact on the stock can be influenced by the quality of the system design but equally importantly the knowledge and experience of the RAS manager. D'Orbcastel *et al*. (2009) evaluated RAS trout farms and they have noticed that the sedimentation system showed a good but highly variable removal efficiency (60%) such that the remaining suspended solids are circulated and degraded in the system. This results in sedimentation areas in other regions of the RAS and general water quality degradation.

The efficiency of biofilter was also variable due to lack of control on temperature. Due to excessive suspended solids, it may disturb the N_2 cycle and can lead directly to nitrite toxicity and mass mortality (Mirzoyan *et al.,* 2010). Accumulation of nutrients and dissolved organics materials originating from uneaten feed and fish faeces can create a favourable environment to a diverse range of bacteria, protozoa, micrometazoa, dinoflagellates and fungi that can alter the water quality and subsequently the stock (Moestrup *et al.,* 2014; Michaud *et al*., 2006).



Water flows from rearing tanks-drum filter-sump 1 - trickling filter-sump; 2 - rearing tanks. One parallel flow across the denitrification reactor, using only faecal carbon as energy source, flows from the drum filter - buffer tank - denitrifying reactor - drum filter.

Figure 2: Innovative RAS using denitrification (USB) reactor (Martins *et al.*, 2010)

Parasites in RAS

Both low and high-tech RAS farms may become infected with pathogens irrespective of the level of control over water quality and despite biosecurity precautions. Even the most efficiently operated farms may eventually become contaminated by a range of monogenean, protozoan and dinoflagellate parasites. According to the design of the RAS farm and technology used, farms infected with parasites may still have the potential to infect recipient waters according to the manner or efficiency of farm effluent management. The most commonly occurred parasites in RAS system are several ciliated protozoan species e.g. *Trichodina spp., Apiosoma sp., Ambiphrya sp., Epistylis sp., Chilodonella piscicola and Icthyobodo necator*. Other more complex parasites of trout include *Spironucleus salmonis* (Diplomonadida), *Gyrodactylus derjavinoides* (monogenean platyhelminthe) and the eye fluke *Displostomum spathaceum* (digenean). Jorgensen *et al.* (2009) reported that these parasites were introduced to the RAS farms by fingerlings supplied from traditional earth ponds. In Danish and Europe, different marine RAS farms infested by

Luciella masanensis, fish mortality increased dramatically despite treatment of the water with peracetic acid and chloramine-T. In another brackish water RAS farm infected by *Pfiesteria shumwayae,* the water was treated with chloramine-T, which caused the dinoflagellates to disappear temporarily from the water column, apparently forming temporary cysts.

Table 1: Major design parameters for RAS (Source: Francis Murray, John Bostock (University of Stirling) and David Fletcher (RAS Aquaculture Research Ltd, 2014)

Parameter	**Comments**
Salinity	This will depend on the requirements of the species, but marine systems have inherently more complex water chemistry and less efficient biofiltration.
Biomass & feed rate	It provides the information about the variation in biomass and the quantity of feed introduced to the system each day is generally the most important factor for system sizing.
Stock density	This is highly dependent on species selected, size range and water quality parameters, tank dimensions and perhaps water flow dynamics. Higher stocking densities generally imply more efficient utilisation of tank volume and overall facilities.
Production plan	The use of multiple batches involving staggered stocking and harvesting schedules is normal in RAS to optimise use of resources and maintain reasonably stable biomass.
Water flow rates	These may be calculated in relation to biomass has been stocked as to provide a consistent supply of water per minute per kg or stock. Consideration of water velocities in relation to body length can be a useful design parameter.
Feed system	This will be specified based on volumes and feed rates required.
Biosecurity	A risk assessment needs to be carried out that considers factors such as species, potential pathogens, disease susceptibility, location and potential routes of infection. This will lead to decisions on disinfection and other biosecurity measures.
Water quality targets	Typical parameters include suspended solids, dissolved oxygen and carbon dioxide, ammonia, nitrite and nitrate, pH, alkalinity, salinity and temperature need to be set at the design stage to help define performance requirements for treatment equipment.
Monitoring & control	Computerised control systems can both help to reduce labour requirements and improve response to out of range conditions. Requirements for system monitoring will be based on design the criteria and water quality targets set, together with a risk assessment of potential points of system failure.
Waste treatment and disposal	The major waste stream from RAS is organic solids which frequently need dewatering and other treatment prior to disposal.

Harmful Algal Blooms (HABs) in RAS

Some of the HABs species is directly parasitic, while the other species can impact stock through released of harmful toxins within the RAS or in the source waters. The broad chemical and structural diversity of algal toxins coupled with differences in intrinsic potency and their susceptibility to biotransformation, account for many of the challenges associated with the detection of these compounds (Yanong, 2009). Technology capable of detecting HABs or toxic by-products would be a critical development for RAS holding high biomass loads at elevated stocking densities. Moreover, treatment of raw water prior to entering the RAS facility is a critical component of RAS design in farms exposed to potential HAB blooms.

Microbial pathogens in RAS system

The RAS unit without or with poor disinfection facilities (UV and ozone) can be susceptible to potential microbial pathogens infestation like bacteria, viruses and fungi can cause severe threats to RAS unit. The most commonly occurring bacteria that increase in numbers in recirculating systems include *Aeromonas spp*., *Vibrio spp*., *Mycobacterium spp*., *Streptococcus spp*., and *Flavobacterium spp*. (Yanong, 2009). Interestingly, some viruses such as IPNV require dose rates that are 7.5 times higher than most bacteria (Yoshimizu *et al.*, 1986). The most effective precaution against important viral disease is probably ensuring eggs, larvae or fry are obtained from specific pathogen free facilities and implementing strict biosecurity measures. The use of up to 2 ppt salinity in addition to UV or ozone disinfection has been found to help minimise this problem. When chemical treatments are added to RAS water the biofilters are often exposed to a high concentration of the chemical which facilitates the risk of impairing the nitrifying microbial population and hence reduce performance of biofilter (Schwartz *et al.,* 2000).

Table 2: Comparison of environmental sustainability indicators for a hypothetical 100 MT/year intensive tilapia farm with conventional RAS and RAS using a denitrification reactor (Eding *et al*., 2009)

Parameters	Conventional RAS	Denitrification RAS
Resource Use		
Fingerlings (#/kg)	1.2	1.2
Feed (kg/kg)	1.22	1.22
Electricity (kWh/kg)	1.8	2.2
Water (L/kg)	238	38
Bicarbonate (g/kg)	252	107
Waste discharge		
N_2 Solid (g/kg)	8.5	2.6
N_2 Dissolved (g/kg)	37.4	5.9
P Solid (g/kg)	4.5	7.2
P Dissolved (g/kg)	3.8	1.3
COD Solid (g/kg)	189	84
COD Dissolved (g/kg)	40	9
TOD Solid (g/kg)	227	95
TOD Dissolved (g/kg)	48	11
TDS (g/kg)	62	28

New advancement in RAS technologies

In conventional RAS, mainly mechanical waste removal and biofiltration units are used for water treatment which has a smaller environmental impact (eutrophication) than flow-through systems. Recent advancement in RAS such as denitrification reactors, sludge thickening technologies and ozone treatments results in minimal use of water, waste discharge and energy use (Martins *et al.,* 2010). Further, discharged water can be easily re-used as fertilizer or in integrated complex improving the environmental sustainability of RAS. Conventional RAS operates at a rate of water refreshment of 0.1-1 m^3/kg feed (Eding and Kamastra, 2002). In recent times, sludge denitrification reactors are used successfully in RAS system (Martins *et al.,* 2009) (Fig. 2). This upflow sludge reactors are anoxic in nature fed with dissolved and particulate faecal organic waste which are digested by denitrifying bacteria present in sludge bed. The organic wastes, bacterial flocs enter the reactor at the bottom and were designed in such a way that the upflow velocity is less than the settling velocity to form the sludge bed at the bottom. In comparison to conventional RAS, this advanced technology reduces water consumption, NO_3, increases alkalinity allowing fish culture in neutral pH and reduces organic matter release. Further in a comparison study, it was found that RAS with denitrification have production cost/kg harvested fish are approximately 10% lower than the conventional RAS (Eding *et al.,* 2009).

Another advancement of RAS culture is use of sludge thickening technologies to reduce the volume of solids produced (Schneider *et al.,* 2006). Sludge thickening technologies includes belt-filter systems and geotextile bags or rubber. In geotextile bag filters, total suspended solids are dewatered before release because of leaching of dissolved organic matter and COD. Use of geotextile bags results in the conversion of solid waste into dry matter by 10% after dewatering for a week. Though the process is more expensive than conventional RAS but it has the advantage of considerable removal of P from aquaculture effluents leading to sustainable aquaculture production (Rishel and Ebeling, 2006). Use of ozonation and UV treatment in RAS improves filtration and reduces the accumulation of organic matter (Summerfelt *et al.,* 2009). There is a rich documented literature on use of ozone in combination with UV treatment to control complete heterotrophic and coliform bacteria counts in freshwater RAS (Sharrer and Summerfelt, 2007).

Recent approach of Integrated RAS culture

In recent times, wetlands and algal ponds has paved attention in integration with RAS as water treatment unit. Effluents and organic wastes released from RAS are in dilute concentration as compared to municipal and domestic house hold wastes. Constructed wetlands use wetland vegetation, soils, and their associated microbial assemblages to treat wastes by concentrating in a particular point (Kerepezki *et al.*, 2003). It is reported that horizontal sub-surface type of constructed wetlands is widely used in aquaculture and can reduce significantly large amount of BOD and organic matter. Vertical flow constructed wetlands is provided with partial recirculation which increases nitrogen removal by denitrification (Aries *et al.*, 2005). Plant species present in wetlands help in removal of organic matter and N_2 while sediments aid in removal of P (Cheng *et al.*, 2009). Integrated RAS culture with constructed wetlands in different parts of country are still in nascent stage. The major advantage of integrated culture includes increase in fish production/m^3 and higher reduction in organic wastes. Sindilariu *et al.* (2009) found 64% of particulate matter, 92% of NO_2 and 81% of NO_3 were removed by using sub-surface constructed wetland in combination with screen filtration.

Microalgae-based water treatment is used for removal of COD and BOD, nutrients, heavy metals and pathogens, and anaerobic digestion of algal-bacterial biomass (Munoz and Guieysse, 2006). High rate algal ponds (HRAPs) are low-energy waste water treatment plants found to remove BOD up to 175 g /m^3/day, compared to 5–10 g BOD for normal (waste stabilization) ponds (Racault and Boutin, 2005). A slightly modified concept of HRAPs was used for waste treatment in partitioned aquaculture systems (PAS) (Brune *et al.,* 2003). In France, a HRAP was integrated with RAS for sea bass as a secondary waste water treatment to reduce the discharge of nutrients from the system (Deviller *et al.*, 2004; Metaxa *et al.*, 2006). It was found that HRAP treated RAS water had better survival rate of fishes in comparison to conventional RAS system. Further, the amount of N_2 and P was found to be less in the rearing water of the RAS + HRAP system signifying higher control over eutrophication than conventional flow-through systems.

Future Prospects in RAS

Climate change, scarcity of fresh water and sudden out breaks of diseases are issues pose a severe threat to future aquaculture industry. World population is growing at a pace of 1.1 % per year and expected to reach 8.5 billons by the end of 2030. FAO projected 1.8 percent increase in the per capita consumption of food fish by 2030. This will put additional burden on the farm production as marine capture fisheries are also expected to decline over the period of time due to over fishing. To keep the present growth of aquaculture industry, an innovative approach is needed to address all those issues. Re-circulatory aquaculture system being a highly intensive culture technique uses very little amount of fresh water and facilitates full control over disease outbreak and other external environmental factors affecting the fish culture. With RAS, 30-50 times more fish production is possible per unit area compared to traditional fish farming with limited use of water.

Financial aspect of RAS is the major need to address before adopting into commercial scale. As per study conducted by Badiola *et al.* (2012), it took more than eight years to get back the return on investment in more than 80% of the cases. Higher initial investment and longer duration of payback period generates lack of interest among the investors. Efforts are required to minimize the cost per unit production and operational cost. Effective use of by-products and development of new energy sources are key ideas in meeting future challenges to generate sustainable blue economy.

CONCLUSION

In spite of several advantages, this system is yet to reach to the large section of the people mostly because of lack of expertise, higher initial investment and high operating cost of running biofilter. Most of the RAS systems are limited to developed countries currently using for either brood stock management or in nursery rearing. Researches are being carried out by the scientists to minimize the operational cost and find suitable species for production. Thorough research and deeper understanding are required to understand the micro ecosystem of RAS and interaction of various component of this species to face the challenges in the future.

REFERENCES

Abeysinghe, D.H., A. Shanableh and B. Rigden. 1996. Biofilters for water reuse in aquaculture. *Water science and technology*, 34(11): 253-260.

Arias, C.A., H. Brix and E. Marti. 2005. Recycling of treated effluents enhances removal of total nitrogen in vertical flow constructed wetlands. *Journal of Environmental Science and Health Part A* 40: 1431–1443.

Attramadal, K.J., I. Salvesen, R. Xue, G. Øie, T.R. Størseth, O. Vadstein and Y. Olsen. 2012. Recirculation as a possible microbial control strategy in the production of marine larvae. *Aquacultural Engineering*, *46*: 27-39.

Badiola, M., D. Mendiola and J. Bostock, 2012. Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. *Aquacultural Engineering*, 51: 26-35.

Blancheton, J.P. 2000. Developments in recirculation systems for Mediterranean fish species. *Aquacultural engineering*, 22(1-2): 17-31.

Brune, D.E., G. Schwartz, A.G. Eversole, J.A. Collier and T.E. Schwedler. 2003. Intensification of pond aquaculture and high rate photosynthetic systems. *Aquacultural Engineering*, 28, 65–86.

Chen, S., Z. Ning and R.F. Malone. 1996. Aquaculture sludge treatment using an anaerobic and facultative lagoon system. In *International Conference on Recirculation Technology, Roanoke, Virginia, Virginia-Tech*.

Cheng, X.Y., W.Y. Chen, B.H. Gu, X.C. Liu, F. Chen, Z.H. Chen, X.Y. Zhou, Y.X. Li, H. Huang and Y.J. Chen. 2009. Morphology, ecology, and contaminant removal efficiency of eight wetland plants with differing root systems. *Hydrobiologia*, 623: 77–85.

Colt, J. 2006. Water quality requirements for reuse systems. *Aquacultural Engineering*, 34(3): 143-156.

David, J.A. 2006. Water quality and accelerated winter growth of European catfish using an enclosed recirculating system. *Water and Environment Journal*, 20(4): 233-239.

Delabbio, J., B.R. Murphy, G.R. Johnson and S.L. McMullin. 2004. An assessment of biosecurity utilization in the recirculation sector of finfish aquaculture in the United States and Canada. *Aquaculture*, 242(1-4):165-179.

Deviller, G., C. Aliaume, M.A.F. Nava, C. Casellas, J.P. Blancheton. 2004. High-rate algal pond treatment for water reuse in an integrated marine fish recirculating system: effect on water quality and sea bass growth. *Aquaculture,* 235: 331–344.

d'Orbcastel, E.R., J.P. Blancheton and J. Aubin. 2009. Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment. *Aquacultural Engineering*, 40(3):113-119.

Eding, E., M. Verdegem, C. Martins, G. Schlaman, L. Heinsbroek, B. Laarhoven, S. Ende, J. Verreth, F. Aartsen, V. Bierbooms. 2009. Tilapia farming using recirculating aquaculture systems (RAS) – case study in the Netherlands. Handbook for Sustainable Aquaculture. Project no.: COLL-CT-2006-030384, http://www.sustainaqua.org.

Eding, E.H. and A. Kamstra. 2002. Netherlands farms tune recirculation systems to production of varied species. Global Aquacult. Advocate 5, 52–54

FAO. 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals. Rome. Licence: CC BY-NC-SA 3.0 IGO

Good, C., J. Davidson, C. Welsh, B. Brazil, K. Snekvik and S. Summerfelt. 2009. The impact of water exchange rate on the health and performance of rainbow trout Oncorhynchus mykiss in water recirculation aquaculture systems. *Aquaculture*, 294(1-2): 80-85.

Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas and C. Toulmin. 2010. Food security: the challenge of feeding 9 billion people. *Science*, 327: 812–818.

Guttman, L. and J. van Rijn. 2008. Identification of conditions underlying production of geosmin and 2-methylisoborneol in a recirculating system. *Aquaculture*, 279(1-4): .85-91.

Jørgensen, T.R., T.B. Larsen and K. Buchmann, 2009. Parasite infections in recirculated rainbow trout (*Oncorhynchus mykiss*) farms. *Aquaculture*, 289 (1): 91–94.

Kerepeczki, A., D. Gal, P. Szabó and F. Pekár. 2003. Preliminary investigations on the nutrient removal efficiency of a wetland-type ecosystem. *Hydrobiologia*, 506: 665–670.

Li, X.L., G. Li, S.Y. Zhang and L. Tao. 2013. Effect of recirculating aquaculture system (RAS) on growth performance, body composition and hematological indicators of allogynogenetic crucian carp (*Carassius auratus gibelio*). *Advance Journal of Food Science and Technology*, 5(3): 348-355.

Losordo, T.M., M.P. Masser and J. Rakocy. 1998. Recirculating aquaculture tank production systems. *Overview of Critical Considerations. SRAC Publication, 451*.

Martins, C.I., M.G. Pistrin, S.S. Ende, E.H. Eding and J.A. Verreth. 2009. The accumulation of substances in Recirculating Aquaculture Systems (RAS) affects embryonic and larval development in common carp Cyprinus carpio. *Aquaculture*, 291(1-2): 65-73.

Martins, C.I.M., E.H. Eding, M.C. Verdegem, L.T. Heinsbroek, O. Schneider, J.P. Blancheton, E.R. d'Orbcastel and J.A.J. Verreth. 2010. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. *Aquacultural Engineering*, 43(3): 83-93

Martins, C.I.M., D. Ochola, S.S.W. Ende, E.H. Eding and J.A.J. Verreth. 2009. Is growth retardation present in Nile tilapia Oreochromis niloticus cultured in low water exchange recirculating aquaculture systems? *Aquaculture*, 298: 43–50

Masser, M.P., J. Rakocy and T.M. Losordo. 1999. Recirculating aquaculture tank production systems. *Management of recirculating systems. SRAC Publication, 452*.

Metaxa, E., G. Deviller, P. Pagand, C. Alliaume, C. Casellas, J.P. Blancheton. 2006. High rate algal pond treatment for water reuse in a marine fish recirculation system: water purification and fish health. *Aquaculture*, 252: 92–101.

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

Michaud, L., J.P. Blancheton, V. Bruni and R. Piedrahita. 2006. Effect of particulate organic carbon on heterotrophic bacterial populations and nitrification efficiency in biological filters. *Aquacultural Engineering*, 34:224–233.

Moestrup, Ø., G. Hansen, N. Daugbjerg, N. Lundholm, J. Overton, M. Vestergård, S.J. Steenfeldt, A.J. Calado and P.J. Hansen. 2014. The dinoflagellates Pfiesteria shumwayae and Luciella masanensis cause fish kills in recirculation fish farms in Denmark. *Harmful Algae*, 32: 33-39.

Munoz, R., B. Guieysse. 2006. Algal-bacterial processes for the treatment of hazardous contaminants: a review. *Water Res*earch, 40: 2799–2815

Murray, F., J. Bostock and D. Fletcher. 2014. Review of recirculation aquaculture system technologies and their commercial application.

Racault, Y., and C. Boutin. 2005. Waste stabilisation ponds on France: state of the art and recent trends. *Water Science and Technol*ogy, 51: 1–9.

Rishel, K.L. and J.M. Ebeling. 2006. Screening and evaluation of alum and polymer combinations as coagulation/flocculation aids to treat effluents from intensive aquaculture systems. *Journal of world aquaculture society,* 37: 191–199.

Schneider, O., J.P. Blancheton, L. Varadi, E.H. Eding and J.A.J. Verreth. 2006. Cost price and production strategies in European recirculation systems. Linking Tradition & Technology Highest Quality for the Consumer. WAS, Firenze, Italy.

Schwartz, M.F., G.L. Bullock, J.A. Hankins, S.T. Summerfelt and J.A. Mathias. 2000. Effects of Selected Chemotherapeutants on Nitrification in Fluidized-Sand Bioftlters for Coldwater Fish Production. *International Journal of Recirculating Aquaculture*, 1(1).

Sharrer, M.J. and S.T. Summerfelt. 2007. Ozonation followed by ultraviolet irradiation provides effective bacteria inactivation in a freshwater recirculating system. *Aquacultural Engineering,* 37, 180–191.

Sindilariu, P.D., A. Brinker and R. Reiter. 2009. Waste and particle management in a commercial, partially recirculating trout farm. *Aquacultural Engineering,* 41: 127–135.

Sugita, H., H. Nakamura and T. Shimada. 2005. Microbial communities associated with filter materials in recirculating aquaculture systems of freshwater fish. *Aquaculture*, 243(1-4): 403-409.

Summerfelt, S.T., M.J. Sharrer, S.M. Tsukuda and M. Gearheart. 2009. Process requirements for achieving full-flow disinfection of recirculating water using ozonation and UV irradiation. *Aquacultural Engineering*, 40(1): 17-27.

Summerfelt, S.T., M.J. Sharrer, S.M. Tsukuda, M. Gearheart. 2009. Process requirements for achieving full-flow disinfection of recirculating water using ozonation and UV irradiation. *Aquacultural Engineering*, 40, 17–27.

Suzuki, Y., T. Maruyama, H. Numata, H. Sato and M. Asakawa. 2003. Performance of a closed recirculating system with foam separation, nitrification and denitrification units for intensive culture of eel: towards zero emission. *Aquacultural Engineering*, 29(3-4):165-182.

Tal, Y., H.J. Schreier, K.R. Sowers, J.D. Stubblefield, A.R. Place and Y. Zohar. 2009. Environmentally sustainable land-based marine aquaculture. *Aquaculture*, 286(1-2): 28-35.

Theodorou, J. A. 2002. Current and future technological trends of european Seabass Seabream culture. *Reviews in Fisheries Science*, 10(3-4): 529-543.

Valtonen, E.T. and A.L. Keränen 1981. Ichthyophthiriasis of Atlantic salmon, *Salmo salar* L., at the Montta hatchery in northern Finland in 1978–1979. *Journal of Fish Diseases*, 4(5): 405-411.

Van Rijn, J. and Y. Barak. 1998. July. Denitrification in recirculating aquaculture systems: from biochemistry to biofilters. In *The Second International Conference on Recirculating Aquaculture, Cooperative Extension/Sea Grant, Virginia Tech, Blacksburg, Virginia* (179-187)

Van Rijn, J., Y. Tal and H.J. Schreier. 2006. Denitrification in recirculating systems: theory and applications. *Aquacultural engineering*, 34(3): 364-376.

Yanong, R.P. 2009. Fish health management considerations in recirculating aquaculture systems. 1: 1-9.

Yoshimizu, M., H. Takizawa and T. Kimura. 1986. UV susceptibility of some fish pathogenic viruses. *Fish Pathology,* 21(1): 47-52.

Timmons, M.B., J.M. Ebeling, N.R.A. Center. 2010. Recirculating Aquaculture. Cayuga Aqua Ventures Ithaca, NY.

How to cite this article?

Aich, N., Nama, S., Biswal, A., Paul, T., 2020. A review on recirculating aquaculture systems: challenges and opportunities for sustainable aquaculture. *Innovative Farming* 5(1): 17-24. .