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REVIEW

Recirculating Aquaculture System (RAS) towards emerging whiteleg shrimp (*Penaeus vannamei*) aquaculture

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Abstract Whiteleg shrimp is one of the most sought-after fishery commodities in the aquaculture sector due to its expensive price, good taste, and disease resistance. In response to its high demand, one of the innovations made for whiteleg shrimp culture is the Recirculating Aquaculture System (RAS). The RAS is an aquaculture technology that recycles used water with a filter to remove wastewater products. The use of RAS offers many advantages, namely reducing water turnover, good water quality, and improving the performance of whiteleg shrimp culture. In addition, RAS also reduces the likelihood of disease infection in the shrimp culture. Through this review, we would like to highlight the development of the RAS approach in whiteleg shrimp farming and its effect on cultivation performance.

Keywords Whiteleg Shrimp . Water quality . Aquaculture . Application . Productivity

Introduction

Aquaculture is one of the most important pillars of food security. In 2020, 87.5 million tons of aquatic animals, valued at USD 281.5 million, were produced to fulfil human needs (FAO 2022). The industry's production has seen a great boost by over 600% since 1990 (Ahmed and Turchini 2021). In response to the development, pelleted shrimp diets produced from fish waste like tuna and sardines have garnered great research interest (Valenzuela-Cobos et al. 2019; Guevara-Viejó et al. 2022). The potential of fed system aquaculture is astounding as it can meet human consumption demands without affecting the natural biodiversity of aquatic commodities (Brown and Dorey 2019; Priyashnatha and Edrisinghe 2021). A study from Zambezi Region, Namibia, suggested that aquaculture is the possible solution towards overfishing and fish stock depletion (Gronau et al. 2020). Furthermore, aquaculture is a source of highly nutritious food without time and location constraints (Correia et al. 2020; Navarro-Peraza et al. 2019). A previous study in 163 countries revealed that there is a positive association between aquaculture production and aquatic food consumption (Garlock et al. 2022). The aquaculture sector continues to grow alongside the development of techniques and cultivated commodities (Campo and Zuniga-Jara 2018; Wardhana et al. 2021), among which is a unique approach known as the Recirculating Aquaculture System (RAS).

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RAS is an aquaculture technology that recycles water with a filter that removes wastewater products (Roques et al. 2021) which will convert toxic compounds such as ammonium, solid waste, and CO_2 into non-toxic compounds to be used again in the pond. This technology is advantageous as it does not require much land, reduces water while enabling high stocking density, and reduces waste such as feces, uneaten feed, or organic matter in the water column (Indriastuti et al. 2022; Xiao et al. 2019). A previous study revealed that RAS could reduce 90-99% of water consumption and reduce ammonia concentration by up to 0.46 gm^2/day (Gichana et al. 2018). The RAS method also resulted in good growth performance, survival rate, and production (Stevčić et al. 2020; Wang et al. 2019). A study of *Ictalurus punctatus* and *Spinibarbus sinensis* aquaculture showed better specific growth rate, final weight, yield, and survival rate in the recirculated pond than in the non-recirculated pond (Zhang et al. 2011). RAS technology has been applied to marine, brackish, and freshwater commodities (Chang et al. 2019; Fossmark et al. 2020; Lorgen-Ritchie et al. 2021) and more recently, to whiteleg shrimp or vannamei shrimp (*Penaeus vannamei*) cultivation.

The whiteleg shrimp is an important economic commodity across the globe. Data from 2018 stated that whiteleg shrimp production had reached 3.5 million tons and was even reported to be the most important aquaculture species (GOAL 2018; Bardera et al. 2019). The whiteleg shrimp has many advantages over other shrimps due to its greater disease resistance, faster growth, and high-stress tolerance (Alday-Sanz et al. 2020; Li et al. 2019). It is due to its immense potential that RAS application in whiteleg shrimp cultivation began to garner interest (Bauer et al. 2021; Suantika et al. 2018b). This review highlights the development of the RAS technique on whiteleg shrimp cultivation, touching on the filters utilized along with results on growth parameters, water quality, disease control, and survival rate from relevant studies. We hope this review could be useful for the development of whiteleg shrimp culture, especially in terms of RAS application.

Overview of RAS in shrimp culture

RAS aims to provide a suitable environment for production-intensive fishery commodities, mainly the whiteleg shrimp, through continuous operation and uniform flow rates of water and oxygen, and water levels as these are essential components of aquaculture (Chen et al. 2020; Das et al. 2022). Furthermore, RAS has the advantage of being a more environmentally friendly, adaptable, predictable, sanitary, and highly efficient use of water resources (Suantika et al. 2018b). According to Ahmed and Turchini (2021) RAS are land-based, indoor fishery commodities-rearing facilities in which fishes are stocked in tanks within a controlled environment where filtration is used to purify water through the removal of metabolic wastes before it is recirculated into the system. Mechanical or biological filtration, sterilization, and oxygenation are all used to purify water. They also stated that RAS offers opportunities to improve waste management, reduce water usage, and recycle nutrients.

RAS is an alternative to overcome the problem of limited land. However, it still has aspects of industrial management to consider, which may include products, raw materials, production, marketing, industrial relations, and internal management (Fauzi et al. 2020). Several studies have proven the positive effect of RAS application, which includes reduced water consumption, increased waste and recycled nutrient utilization, and better hygiene-disease management, as reported by Chen et al. (2018). The benefits of RAS points to good potential for developing whiteleg shrimp culture technology through quality and productivity improvement. Whiteleg shrimp, as we know, is the most productive crustacean cultivated because of its high yield, high tolerance, good adaptability, and fast growth (Chen et al. 2020).

The first ever advancements toward completing the life cycle of penaeid shrimp in captivity occurred in 1934 (Chamberlain 2010), followed by the invention of RAS technology, which was introduced back in the 1950s in Japan (Ahmed and Turchini 2021). In 1970, a German program demonstrated the feasibility of intensive carp production in RAS, and subsequently, the Danish Aquaculture Institute undertook an innovative effort to develop further technical aspects of RAS (Goldman 2016). Nowadays, many farmers and researchers have applied RAS technology in whiteleg shrimp culture. The technology is believed to be worthy and can be widely applied to reduce the environmental impact of sewage disposal and the risk of disease contamination from polluted external water supplies (Cheng et al. 2014). According to Zhong et al. (2011) when combined with a constructed wetland system, RAS could be a viable mode for sustainable aquaculture development. When viewed from a hierarchical analytical process perspective, Zulkarnain et al. (2020) stated that RAS technology is most suitable for intensive whiteleg shrimp farming, based on minimum land utilization for whiteleg shrimp farming, locations of brackish water, environmental friendliness, energy consumption, and biosecurity. Furthermore, Suantika et al. (2018b) reported that RAS could be applied for super-intensive whiteleg shrimp culture at an optimal density of 500 PL/m^3, allowing high productivity of up to 5.20 kg/m^3 within 84 days of the grow-out period. Nevertheless, RAS technology still has its challenges in its application, one of them being energy efficiency. It is only with a solution that RAS could continue to support the productivity of whiteleg shrimp culture in the future.

RAS provides an alternative production method when limited by environmental regulations, disease, land availability, salinity, temperature, and water. A recirculating aquaculture system (RAS) can remove metabolic waste from the culture system via water treatment, which includes physical and biological filtration, to realize the utilization of recycled aquaculture water. To achieve that, the system is equipped with a series of water treatment processes, which leads to high water flow and subsequently high energy consumption. Despite that, RAS can effectively convert the metabolic wastes of shrimp, such as ammonia and nitrite, into low-toxicity nitrate, and control ammonia and nitrite within a safe concentration range for shrimp culture. An excessive C/N ratio will inhibit the growth of nitrifying bacteria and the nitrification of the biofilter is mainly conducted by autotrophic nitrifying bacteria (Chen et al. 2020).

A recirculating aquaculture facility reduces water demands and discharges by reconditioning water to be used repeatedly. Thus, better food conversions are achievable with RAS, which also indicates that less waste is generated from the feed. RAS technology can reduce the effluent waste stream by a factor of 500–1000. Recirculating systems are very compatible with the complex nature of reproduction and the brood stock fecundity of most marine species, which can help diminish waste processing costs. It is suggested that the degradation of water quality is detrimental to shrimp growth and survival. With continuous use of RAS technology, stable water quality parameters can be maintained even at high stocking densities of up to 1000 PL/m^3 with high organic load to the system (Suantika et al. 2018b).

RAS and hybrid RAS

RAS has been proven to be effective when applied with existing aquaculture technologies such as constructed wetlands (CWs), biofloc, and multi-trophic aquaculture. Several past studies found potential in a combination of RAS and multi-trophic aquaculture, in which the water is progressively enriched with nutrients generated by shrimp farming where NO_3^- was the nitrogenous form present in the highest concentration, followed by NH_4^+ and NO_2^-. This enrichment pattern was similar to other studies on RAS shrimp farming; the nitrification processes had occurred naturally and led to high nitrate levels while observing a significant increase in PO_4^{3-} concentration in the RAS compartments. Several studies reported that the increase in the concentration of these nutrients can be useful for seaweed production in integrated cultivation, which can also reduce the waste released into the environment. The increase in nutrients was beneficial for the *Gracilariopsis tenuifrons* growth, showing an efficient conversion of shrimp metabolic waste into algal biomass (Carneiro et al. 2021).

The performance of RAS technology in shrimp farming is often evaluated by comparing its economical availability and efficiency against other approaches. In recent years, CWs have been widely used in wastewater treatment and ecosystem restoration. Wastewater purification by CWs is a consequence of physical, biological, and chemical mechanisms. Based on an investigation, a CW and RAS combination could reduce the nitrogen concentration in the pond water to an average of 34%-50% through water recycling in three different aspects: mainly denitrification, wetland substrate (4%) accumulation and plant assimilation (4.12%) (Zhong et al. 2011). With that, the wastewater could be utilized as a culture media for microalgae cultivation to increase system sustainability. Malibari et al. (2018) reported that microalgae could grow effectively in various types of wastewater, which includes discharges from aquaculture hatcheries and farming operations. Apart from its ability to promote microalgae growth, wastewater can increase the availability of useful bioactive compounds for aquatic species like the whiteleg shrimp. Another previous study done by Yang et al. (2010) found that the average dissolved oxygen concentration in the RAS system was about 5.1 mg L^{-1} with the TAN concentration between 0.002-0.15 mg L^{-1} and pH levels ranging from 7.62-8.29 after about 90 days. The culture test returned good results with the final shrimp output being about 4.6 kg/m^2 with a low cost of raising 1 kg shrimp with 1000 L water and 2.16 kWh electricity cost. The seven criteria assessed before implementation are affordability of capital and mini-scale operational costs, minimum land area required for shrimp farming, dependence on raw water source locations, environmentally friendly, productivity, energy consumption, and biosecurity. A comparison between existing intensive shrimp farming technology (biofloc technology, supra intensive, shrimp farming in mini scale with tarpaulin/High-Density Polyethylene (BUSMETIK-HDPE), and RAS) showed that the most suitable technology for intensive whiteleg shrimp farming was RAS. RAS is advantageous for shrimp farming as it could utilize brackish water sources, requires minimum land area, is environmentally friendly with lower electrical consumption, and provides biosecurity (Zulkarnain et al. 2020).

Specifications of RAS

RAS can be defined as an aquaculture system that incorporates the treatment and reutilization of water with less than 10% of the total water volume replaced per day. The concept of RAS is to reuse and deliver a volume of water following continual treatment to cultured organisms. Water treatment components used in RAS need to accommodate the high input of feed required to sustain high growth rates and high stocking densities necessary to achieve financial outcomes. Generally, RAS consists of mechanical and biological filtration components, pumps, and holding tanks and may include several additional water treatment elements that improve water quality and provide disease control within the system (Rekha et al. 2018). In general, the components of RAS can consist of a solid waste removal unit, biological filtration unit, degassing and oxygenation unit, and a disinfection unit.

To start with, RAS is equipped with membrane filter technology as an alternative solution for water management in shrimp farming in addition to the employment of ecological methods and biological or chemical substances. Membrane technology can be introduced into the aquaculture industry for pond water conditioning and wastewater treatment before discharging into the ecosystem (Qin et al. 2005). Microfiltration (MF) membrane possesses pore sizes ranging from 0.1 to 100 µm. Ultrafiltration processes have been extensively employed for various applications such as water treatment (Qu et al. 2014). In recent years, ultrafiltration membranes have been further explored for their efficiency in virus removal (ElHadidy et al. 2013). This has shed some light on the use of UF membranes as means of disease control in the shrimp farming industry due to their lower operating cost compared to nanofiltration (NF) or reverse osmosis (RO) processes.

Membrane technology offers a possible solution to improve aquaculture pond water quality in an effort to minimize the mortality rate of cultured stocks. Membrane technology can also possibly reduce the impact of shrimp farming on the environment by reducing the contaminants in the system discharges, which may have resulted from excessive use of biological and chemical products like herbicides, pesticides, antibiotics, and salinity-controlling agents. During shrimp farming activity, there is frequent exchange between surrounding water and pond water to ensure well-maintained water quality. The discharged pond water has

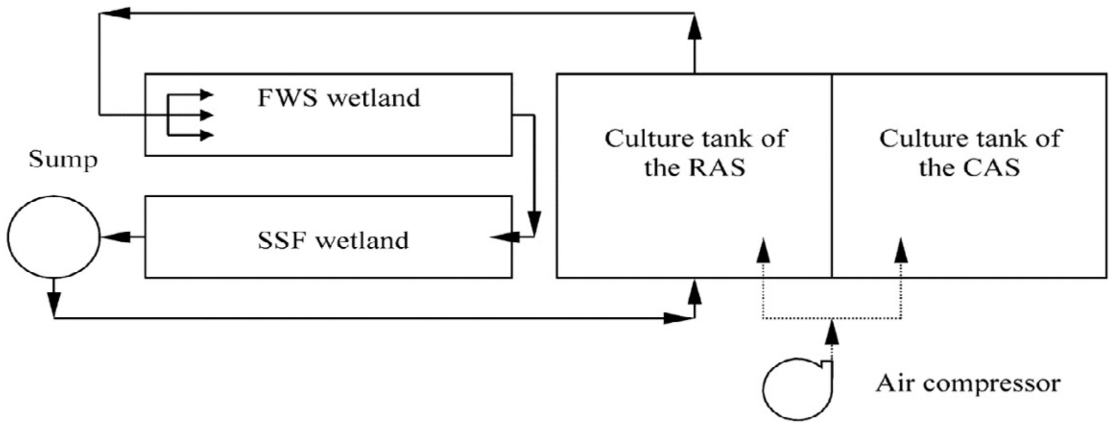

Fig. 1 The simple illustrations of RAS (Lin et al. 2003). FWS: Free water surface flow, SSF: Subsurface flow, CAS: Control culture system. Water from the shrimp culture is pumped to the FWS and purified or treated there. After that, the water that has been treated continues to be purified in SF using river stones and then pumped back through the sump and air compressor to the shrimp pond.

been associated with several environmental issues such as eutrophication, depletion of dissolved oxygen, and siltation due to the high content of suspended solids and nutrients (as high as 46.6 µM of ammonium, 3.0 µM of phosphate, 9.2 µM of nitrate, 6.1 µM of nitrite, etc.) (Herbeck et al. 2013).

In RAS, the removal of ammonia and nitrite-nitrogen must be at the same rate as its production to maintain a stable culture environment. Biological filtration (biofiltration) is the most used method to control ammonia. Its mechanism is based on the oxidation of ammonia to nitrite, and finally into the less toxic nitrate by two groups of bacteria— *Nitrosomonas* (ammonia) and *Nitrobacter* (nitrite to nitrate) (Losordo et al. 1994).

The most common nitrogen removal approach in RAS is through utilizing Fluidized Bed Filters. These are essential mechanical sand filters operated continuously in the expanded (backwashing) mode so that the sand media becomes fluidized. An up flow of pressurized water keeps the sand grains in motion and not in continuous contact with one another, which provides an excellent substrate for nitrifying bacteria to colonize. (Weirich et al. 2002).

Ozone is used in RAS as a disinfectant to remove organic carbon, turbidity, algae, color, odor, and taste (Goncalves and Gagnon 2012). Ozone is efficient in eliminating most pathogens affecting seafood in freshwater and seawater aquaculture, especially in whiteleg shrimp culture. Moreover, ozone can improve water quality by reducing biochemical oxygen demand (BOD) (Sharrer and Summerfelt 2007). Ozone can be applied continuously as a series of treatments per day or as a single batch treatment per day (Rakness 2005). Application in most situations can be dependent on the feeding strategy employed in the culture system. Single-batch ozone treatment can be used to target rises in waste levels in the system associated with a moderate feed event or to treat batches of exchange or inlet water from the supply source. The required amount of ozone for treatment in a RAS is usually calculated according to the daily feed rate. Rates of 10–15 g ozone per kg feed are generally recommended to reduce accumulated organics. Any background organic loadings of the source water used for RAS should also be considered (King 2001).

The application of ozone within aquaculture systems requires ozone generation, ozone dissolution, contact time for ozone reaction, and possibly ozone destruction to prevent ozone residuals in the culture tanks (Sharrer and Summerfelt 2007). In RAS, some designs are also used for oxygen transfer or aeration. In freshwater, ozone decomposes rapidly to oxygen after application. By introducing ozone in aquacultural seawater systems, a series of redox reactions take place to form several reactive intermediates (Liltved et al. 2006). Effective transfer of ozone into water is important because the production cost of ozone is significant, especially if it is carried within purified oxygen feed gas that is either purchased or produced on-site. The rate of ozone transfer and the subsequent rate of ozone decomposition depends on the contact system efficiency and the reaction rates of ozone with water constituents. The ozone reaction rate depends on the water temperature along with the concentration and type of constituents in the water. (Summerfelt et al. 2004). Ozone is used in aquaculture systems to improve water quality and overall system performance (King 2001). Ozonation has proven useful in aquaculture systems as it promotes the removal of solid matter (Tango and Gagnon 2003.) Reuter and Johnson (1995) found that the use of ozone before sedimentation or filtration improved the removal of suspended solids and concluded ozone's multiple uses for disinfection, water aeration, and removal of metabolic by-products. They have also noted improvements in suspended solids removal as presented in this and another research, making it an especially appropriate treatment process for hatcheries.

Environmental parameters such as water temperature, salinity, dissolved oxygen (DO), and pH play a vital role in the entire shrimp culture process. Changes in their values have important effects on shrimp physiology, particularly on its growth, metabolism, reproduction, and molting. In most previous studies, the water quality parameter for shrimp cultures such as TAN, NO_3^{-N}, and NO_2^{-N} remain at a safe level in RAS ponds. The biofilter technology used in RAS could maintain a high-quality water environment with sufficiently low ammonium concentration while processing TAN at an adequate level (Kumar et al. 2010), showing that biofilters can reduce the amount of ammonia in shrimp culture successfully. RAS typically employ a biofilter to control ammonia levels produced as a by-product of fish protein catabolism. *Nitrosomonas* (ammonia-oxidizing), *Nitrospira*, and *Nitrobacter* (nitrite-oxidizing) species are thought to be the primary nitrifiers present in RAS biofilters.

Another study done by Fleckenstein et al. (2022) mentioned that pH levels in the RAS system could be maintained by using artificial materials such as low-cost salt (LCS). The pH levels were maintained when using the LCS as a complete sea salt mixture would include multiple buffers, such as calcium, potassium, and magnesium carbonate compounds. Commercial producers utilizing indoor RAS and biofloc use culture water formulated with LCS throughout their entire production cycle (Galkanda-Arachchige et al. 2020). In another study by Du et al. (2021) the temperature, DO and salinity all remained within acceptable ranges for the growth of *L. vannamei* when using RAS. The pH level between 7.9 and 8.1 reported indicates that the intended effect of the treatment's extra filtration was successful as particle concentration was kept low. In this study, the ammonia concentration remained consistently high while nitrite levels had decreased below 1 mg L^{-1} NO_2^{-N} in the RAS. Nitrate concentration did not appear to accumulate as expected in systems with a functioning nitrifying bacterial community (Andrew et al. 2017).

Furthermore, the implementation of RAS can curb water pollution caused by organic material too. Coastal shrimp culture constantly uses copper sulfate to eradicate algae during the production cycle. RAS technology has been proven to lower the probability of copper contamination in shrimp cultures. One study found that the RAS system could maintain the COD, $NH4^{-N}$ and $NO2^{-N}$ levels along with the number of heterotrophic bacteria, ammonium-oxidizing bacteria, and nitrite-oxidizing bacteria in the biofilm as the Cu^{2+} concentration was decreased to 0.089 ± 0.012 mg L^{-1} upon harvest. This indicates that the RAS can work well and supply safe food shrimp containing under 0.3 mg L^{-1} copper in a three-month culture period (Cheng et al. 2011).

Growth performance

Growth performance is one of the parameters used to determine the effectiveness of RAS application in whiteleg shrimp culture. A number of growth aspects can be evaluated to determine the successful performance of whiteleg shrimp. A review of growth performance results from several sources is listed in Table 1. Du et al. (2021) found an increase in the final weight from 0.4 g to 13.43 g in whiteleg shrimps that were reared in a RAS system for 53 days. Meanwhile, Chen et al. (2020) obtained a specific growth rate (SGR) of 6.80 g with a final weight of 9.75 g in the whiteleg shrimps reared in a RAS system without any treatment. The same trend was also reported by Suantika et al. (2020), where whiteleg shrimps cultured for 90 days in the RAS system could produce SGR and MBW (mean body weight) of 7.12% BW/day and 14.86 g, respectively. Both Suantika et al. (2018b) and Chen et al. (2018) also reported a positive trend in whiteleg shrimps cultured in the RAS system.

Some of the explanations above showed that the usage of the RAS system in whiteleg shrimp farming produces convincing results that support its production. Compared to several other technologies, RAS still has multiple advantages in terms of growth performance. In a study by Suantika et al. (2020) the use of RAS with hybrid zero water discharge (ZWD)-RAS in whiteleg shrimp farming was compared with the results of whiteleg shrimp cultured in a conventional RAS system. The RAS system delivered good growth performance compared to the hybrid ZWD-RAS system, which produced only SGR and MBW of 7.05% BW/day and 12.06 g, respectively. As another example, a study by Al-Ghawari and Al-Buhaishi (2021) on

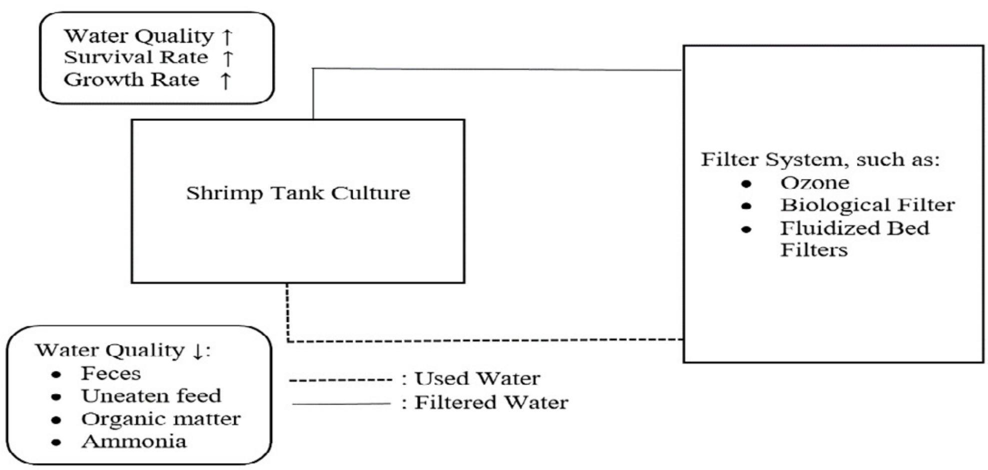

Fig. 2 The RAS mechanism in shrimp aquaculture

Table 1 The growth performance parameter of whiteleg shrimp using the RAS

Type of shrimp culture	Maintenance time (days)	Size	Shrimp density	Specific parameters	Results	References
Recirculating aquaculture system	53	0.4 g	960-1150 m^{-3}	Final weight (g)	13.43	Du et al. (2021)
	121	6 mm	450 ind m^{-3}	Specific growth rate (%/day)	6.80 ± 0.35	Chen et al. (2020)
				Final weight (g)	9.75 ± 3.65	
	90	PL 10	500 ind m^{-3}	Specific growth rate (%BW/day)	7.12 ± 0.01	Suantika et al. (2020)
				Mean body weight (g)	14.86 ± 2.42	
	84	PL 8	500 ind m^{-3}	Specific growth rate (%BW/day)	7.12 ± 0.01	Suantika et al. (2018b)
		PL 8	750 ind m^{-3}		6.95 ± 0.01	
		PL 8	1000 ind m^{-3}		6.79 ± 0.01	
	50	0.87 g ± 0.03	656 ind m^{-2}	Final weight (g)	9.92 ± 1.31	Chen et al. (2018)
Low-cost artificial sea salt mixtures using indoor operations (recirculating aquaculture system)	86	2.9 g	262 shrimp m^{-3}	Growth rate (g/week)	1.4 ± 0.0 – 1.6 ± 0.1	Fleckenstein et al. (2022)
Recirculation system with zero water exchange	29	8.0 g ± 0.04	45 shrimp m^{-2}	Biomass (g)	10.3 ± 1.8	Carneiro et al. (2021)
				Relative growth rate (%/day)	1.7% ± 0.1	
Hybrid zero water discharge-recirculating aquaculture system	90	PL 10	500 ind m^{-3}	Specific growth rate (%BW/day)	7.05 ± 0.05	Suantika et al. (2020)
	84	PL 10	500 ind m^{-3}	Mean body weight (g)	12.06 ± 5.72	Suantika et al. (2018a)
			750 ind m^{-3}		11.84 ± 3.58	
			1000 ind m^{-3}		12.04 ± 3.71	

*PL: Post-larvae, ind: Individual, BW: Body weight. The values shown are cited from several published scientific sources. Data other than RAS is used as support, which can potentially be applied to RAS systems the effects of water exchange and biofloc systems on the growth of whiteleg shrimp had only resulted in SGR values of 2.8133%/day and 3.0200%/day, respectively.

RAS application has positively impacted the growth of whiteleg shrimp through numerous factors. In general, its implementation is expected to maintain good water quality, followed by optimal feed utilization and efficiency, as well as several other crucial factors like stocking density, shrimp quality, and size of rearing media. This is consistent with the findings of Suantika et al. (2018b), which claimed that using the RAS system for a shrimp density of 500 PL/m^3 could achieve high productivity of up to 5.20 kg/m^3 with high feed utilization efficiency while maintaining good water quality throughout an 84-day growth period, pointing to potential to be applied on an industrial scale. The same phenomena were also observed by Du et al. (2021). The existence of RAS marks an important breakthrough in whiteleg shrimp culture as it provides solutions to various challenges, one of which being stocking density, to enable high productivity.

The concept of RAS in terms of growth performance is to reutilize the volume of water through continuous treatment and delivery to the cultured organism as the water component needs to accommodate the high amount of feed input required to attain high growth performance and stocking density (Balasubramanian et al. 2018). A balance between the whiteleg shrimp, pathogens, and the culture environment needs to be achieved for optimal metabolic process and shrimp growth. Nutrition and feeding practices optimized for farm production systems will put super-intensive farming operations in the best possible position for success (Emerenciano et al. 2022).

Survival rate

The survival rate is a key parameter to determine the success of sustainable aquaculture. It is related to major stress factors such as physical factors (water quality and stocking density) and chemical factors (formalin and sanitizers) (Park et al. 2016). The stocking density is one of the most crucial factors behind the survival rate in RAS systems. High stocking density has a high correlation with water quality; RAS systems can provide a stable and controlled environment, especially in terms of water quality, to ensure the survival rate in high stocking density cultures. As such, RAS is regarded as a cost-efficient approach to intensive cultivation. A review of the survival rate in RAS systems from several sources can be found in Table 2.

Previous studies have shown that RAS modification, such as combination with biofloc technology (BFT), utilization of seaweed as a biofilter, ozonation, and low-salinity condition (Ray et al. 2017; Suantika et al. 2018b; Tierney and Ray 2018; and Pumkaew et al. 2021) can improve and maintain the survival rate of shrimp. The combination of RAS with low-salinity conditions has proven to increase the survival rate by up to 70% in high stocking densities of around 500 individuals/m^3 (Suantika et al. 2018a). Super-intensive production involves a stocking density of 500 individuals/m^3 (Suantika et al. 2018b). Super-Intensive aquaculture requires oxygen supplementation. However, the author did not mention the relationship between the oxygen cycle in the high stocking density culture and high oxygen demand. The dissolved oxygen levels in the RAS system are high due to continuous water flow, which allows the shrimp's oxygen needs to be met even in high stocking density. Moreover, a previous study showed that there was no significant difference between the shrimp survival rates of the control (81.6 ± 2.9%) and ozone-treated (80.0 ± 0%) RAS, suggesting that ozone in the concentration of 0.3 mg L^{-1} is safe for shrimp culture (Pumkaew et al. 2021). In addition, the usage of low-cost artificial salt in RAS had no detrimental impact on shrimp performance in increased concentration of LCS (Fleckenstein et al. 2022). This finding can reduce the cost of artificial salt in shrimp culture. Yet, the composition of sea salt should be considered carefully as some salts can contain high impurities, resulting in inadequate concentrations of target minerals or possible toxic effects on shrimp.

A hybrid between the RAS and biofloc systems can enhance the survival rate (Ray and Lotz 2017) because they provide internal biological filtration through nitrification and algal and bacterial assimilation. Yet, the clear water RAS system showed a higher survival rate than that of the RAS-biofloc system due to high particulate concentrations indicated by the turbidity value, which might have increased the oxygen demand of the microbial community (Ray et al. 2017). Despite that, the RAS system is suitable for super-intensive culture as it leaves no significant impact on the survival rate of high shrimp stocking density.

Table 2 The survival rate parameter of whiteleg shrimp using the RAS

Type of shrimp culture	Details	Size	Shrimp density	Results (%)	References
Recirculating aquaculture system	The multi-stage biofilters included 7 tanks (filled with elastic brush media and suspended porous media)	0.87 g	656 m^{-2}	68.97	Chen et al. (2018)
	Biofilter tank consists of 50 kg of limestone gravel and 10 kg of plastic bio-balls	0.01 g	500 m^{-3}	70	Suantika et al. (2020)
Clear water recirculating aquaculture system	It has a settling chamber, a foam fractionator, and an external biofilter Use dechlorinated municipal water mixed with salt	Unexplained	250 m^{-3}	78	Ray et al. (2017)
Recirculating aquaculture system with low-salinity condition	The RAS system consists of settlement tank, protein skimmer, activated carbon tank, biofilter, shrimp culture tank Biofilter consists of bacteria consortium, and also adding by 5 mg L^{-1} of ammonium chloride	Unexplained	500 m^{-3}	70	Suantika et al. (2018a)
Recirculating aquaculture system with ozonation (0.3 mg L^{-1})	A lab-scale brackish RAS integrated with ozonation	0.5 kg m^{-3}	20 juvenile per tank	Safe for shrimp, there was no significant difference between control and tank with ozonation	Pumkaew et al. (2021)
Recirculating aquaculture system with low-cost artificial sea salt (LCS)	The percentage of LCS is 97.5% Biofilters were moving bed biological reactors (MBBR) and contained biological media	Unexplained	262 m^{-3} post-nursery shrimp	84.3 The increased concentration of LCS used in production appears to have no detrimental impact on shrimp performance	Fleckenstein et al. (2022)
Recirculating aquaculture system use sea cucumber nursery tanks	Microfilter consist of 260 mesh nylon screens, MBBR, ozone generator, and the liquid oxygen Dewar tank	0.4 g	1150 m^{-3}	94.95	Du et al. (2021)
Recirculating aquaculture system with agarophyte *Gracilariopsis tenuifrons* as biofilter	Zero exchange water	8 g	45 m^{-2}	100	Carneiro et al. (2021)
Recirculating aquaculture system with biofloc technology	Settling chamber was utilized only if turbidity exceeded 30 NTU Pseudo MBBR not contain any media, but it contained an air diffuser	0.007 g	3000 m^{-3}	86.2 ± 1.7	Tierney and Ray (2018)
	Stand pipers with no opening were placed in the drains to prevent water from entering Source of oxygen from pressurized tanks of oxygen connected to a fine-pore diffuser	2.6 g	250 m^{-3}	61 ± 0.0	Ray and Lotz (2017)

Table 3 The role of RAS as disease control in whiteleg shrimp

Type of shrimp culture	Dose	Density	Remarks	Impacts	References
RAS with ozonation	0.3 mg L^{-1}	20 juvenile per tank (0.5 kg m^{-3})	A lab-scale brackish RAS integrated with ozonation	Control *Vibrio parahaemolyticus* infections effectively without affecting the performance of the nitrification biofilter, thereby achieving a balance between water quality and shrimp safety.	Pumkaew et al. (2021)
RAS with Super-Intensive	Different stocking density	500 ind m^{-3} 750 ind m^{-3} 1,000 ind m^{-3}	Reduce salinity level of 32 ppt to 5 ppt within 14 days (best result: 1,000 ind m^{-3})	Stable community structure of culturable bacteria	Suantika et al. (2018b)
RAS with reduced water salinity	15‰ and 30‰	4 – 5 shrimps per tank	High salinity of 30‰ (best results)	Control *V. parahaemolyticus*	Bauer et al. (2020)
RAS with *U. lactuca*	*U. lactuca* density of 0.5 g L^{-1}	a shrimp per tank	Algae be used as bioremediator	Increase the total probiotic bacteria and reduce total potential pathogens bacteria (*Vibrio* spp.)	Mangott et al. (2020)
RAS with ozonation	5 – 50 mg per hour	20 shrimp per tank	Redox potential in the water was adjusted to 350 mV	Stabilize the microbial composition in the water and the biofilm on the surface of the tank.	Teitge et al. (2020)

Disease control

Worldwide, cultured whiteleg shrimps are frequently affected by various pathogens. These disease-causing agents are responsible for high mortality and can lead to massive economic losses in this industry. Disease outbreaks can result from a complex interaction of multiple factors: deprived culture environment, intensive stocking density with poor management, stress, suppressing host immune system, and virulence of infectious agents like bacteria, viruses, fungi, and parasites (Kennedy et al. 2016). In other words, diseases result from a complex interaction between the host, the pathogen, and the environment. Shrimps are vulnerable to various viral and bacterial infections. The widespread disease in whiteleg shrimp culture has placed studies on preventive approaches as the top priority in aquaculture (Alavandi et al. 2004). A review of shrimp disease from several sources can be found in Table 3. A previous study showed that culturing shrimp in a RAS system modified with ozonation in an appropriate dose can control the abundance of *Vibrio parahaemolyticus* (Pumkaew et al. 2021). Ozone's ability to destroy or inactivate a variety of bacterial, fungal, protozoan and viral germs is the primary advantage of ozonation for controlling undesired microbes, particularly pathogens. Earlier investigations reveal that ozone treatment can curb both bacterial and viral infections successfully. Pathogen loads in shrimp larviculture can be decreased with acceptable ozone use, which will also benefit shrimp survival and growth (Teitge et al. 2020). Another previous study stated that the RAS system can manage the bacterial community in the water to reduce the abundance of pathogenic bacteria (Suantika et al. 2018b). This ability to reduce the number of pathogen bacteria comes from the filtration in the RAS system.

Conclusion

The RAS production approach provides an alternative when limited by environmental regulations, disease, land availability, salinity, temperature, and water. The system can remove metabolic waste from the aquaculture system through water treatment, which includes physical and biological filtration, to realize the utilization of recycled aquaculture water. As such, the RAS system can be a primary consideration for whiteleg shrimp farming to achieve sustainable aquaculture.

Competing interests The authors declare that they have no competing interests.

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References

Ahmed N, Turchini GM (2021) Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. J Clean 297 126604:1-14. https://doi.org/10.1016/j.jclepro.2021.126604

Alavandi SV, Vijayan KK, Santiago TC, Poornima M, Jithendran KP, Ali SA, Rajan JJS (2004) Evaluation of *Pseudomonas sp*. PM 11 and *Vibrio fluvialis* PM 17 on immune indices of tiger shrimp, *Penaeus monodon*. Fish Shellfish Immunol 17(2):115-120. https://doi.org/10.1016/j.fsi.2003.11.007

Alday-Sanz V, Brock J, Flegel TW, McIntosh R, Bondad-Reantaso MG, Salazar M, Subasinghe R (2020) Facts, truths and myths about SPF shrimp in Aquaculture. Rev Aquac 12(1):76-84. https://doi.org/10.1111/raq.12305

Balasubramanian CP, Anand S, Kannappan S, Biju IF (2018) Training manual on recent advances in farming of pacific white shrimp (*Penaeus vannamei*). In: Training Manual Series. ICAR-Central Institute of Brackishwater Aquaculture. https://courseware.cutm.ac.in/wp-content/uploads/2020/06/Vennamei.pdf. Accessed 18 October 2022

Bardera G, Usman N, Owen M, Pountney D, Sloman KA, Alexander ME (2019) The importance of behaviour in improving the production of shrimp in aquaculture. Rev Aquac 11(4):1104-1132. https://doi.org/10.1111/raq.12282

Bauer J, Teitge F, Neffe L, Adamek M, Jung A, Peppler C, Steinhagen D, Jung-Schroers V (2021) Impact of a reduced water salinity on the composition of Vibrio spp. in recirculating aquaculture systems for Pacific white shrimp (*Litopenaeus vannamei*) and its possible risks for shrimp health and food safety. J Fish Dis 44(1):89-105. https://doi.org/10.1111/jfd.13270

Brown C, Dorey C (2019) Pain and emotion in fishes–fish welfare implications for fisheries and aquaculture. Anim Stud J 8(2):175-201. http://dx.doi.org/10.14453/asj.v8i2.12

Campo SR, Zuniga-Jara S (2018) Reviewing capital cost estimations in aquaculture. Aquac Econ Manag 22(1):72-93. https://doi.org/10.1080/13657305.2017.1300839

Carneiro MADA, Resende JFDJ, Oliveira SR, Fernandes FDO, Borburema HDDS, Barbosa-Silva MS, Ferreira ABG, Soriano EM (2021) Performance of the agarophyte *Gracilariopsis tenuifrons* in a multi-trophic aquaculture system with *Litopenaeus vannamei* using water recirculation. J Appl Phycol 33:481-490. https://doi.org/10.1007/s10811-020-02318-7

Chamberlain G (2010) History of Shrimp Farming. https://www.globalseafood.org/advocate/history-of-shrimp-farming/. Accessed

18 October 2022
Chang BV, Liao CS, Chang YT, Chao WL, Yeh SL, Kuo DL, Yang CW (2019) Investigation of a farm-scale multitrophic recirculating aquaculture system with the addition of Rhodovulum sulfidophilum for milkfish (*Chanos chanos*) coastal aquaculture. Sustainability 11(7):1880. https://doi.org/10.3390/su11071880
Chen Z, Ge H, Chang Z, Song X, Zhao F, Li J (2018) Nitrogen budget in recirculating aquaculture and water exchange systems for culturing *Litopenaeus vannamei*. J Ocean Univ China 17(4):905-912. https://doi.org/10.1007/s11802-018-3584-9
Chen Z, Chang Z, Zhang L, Wang J, Qiao L, Song X, Li J (2020) Effects of carbon source addition on microbial community and water quality in recirculating aquaculture systems for *Litopenaeus vannamei*. Fish Sci 86(3):507-517. https://doi.org/10.1007/s12562-020-01423-3
Cheng B, Liu Y, Yang H, Song Y, Li X (2014) Effect of copper on the growth of shrimps *Litopenaeus vannamei*: water parameters and copper budget in a recirculating system. Chin J Oceanol Limn 32(5):1092-1104. http://dx.doi.org/10.1007/s00343-014-3277-1
Cheng B, Liu Y, Yang H, Gao X (2011) Performance of shrimp recirculating aquaculture system with copper polluted. TCSAE 27(2):248-254. doi:10.3969/j.issn.1002-6819.2011.02.042
Correia M, Azevedo IC, Peres H, Magalhães R, Oliva-Teles A, Almeida CMR, Guimarães L (2020) Integrated multi-trophic aquaculture: a laboratory and hands-on experimental activity to promote environmental sustainability awareness and value of aquaculture products. Front Mar Sci 7:156. https://doi.org/10.3389/fmars.2020.00156
Das RR, Sarkar S, Saranya C, Esakkiraj P, Aravind R, Saraswathy R, Rekha PN, Muralidhar M, Panigrahi A (2022) Co-culture of Indian white shrimp, *Penaeus indicus* and seaweed, *Gracilaria tenuispitata* in amended biofloc and recirculating aquaculture system (RAS). Aquaculture 548:737432. https://doi.org/10.1016/j.aquaculture.2021.737432
Du Y, Xu J, Zhou L, Chen F, Qiu T, Sun J (2021) Retrofitting sea cucumber nursery tanks to recirculating aquaculture for highly intensive *Litopenaeus vannamei* aquaculture. Appl Sci 11(20):9478. https://doi.org/10.3390/app11209478
ElHadidy AM, Peldszus S, Dyke MIV (2013) An evaluation of virus removal mechanisms by ultrafiltration membranes using MS2 and X174 bacteriophage. Sep Purif Technol 120:215–223. https://doi.org/10.1016/j.seppur.2013.09.026
Emerenciano MGC, Rombenso AN, Vieira FDN, Martins MA, Coman GJ, Truong HH, Noble TH, Simon CJ (2022) Intensification of penaeid shrimp culture: an applied review of advances in production systems, nutrition and breeding. Animals 12(3):236. https://doi.org/10.3390/ani12030236
FAO (2022) The State of World Fisheries and Aquaculture: Aquaculture Production, Rome. https://www.fao.org/3/cc0461en/. Accessed 11 November 2022
Fauzi RL, Pamungkas AP, Purwadi D (2020) White shrimp *Litopenaeus vannamei* based agroindustry through recirculating aquaculture system to increase competitiveness. E3S web conf. The 3rd International Symposium on Marine and Fisheries Research (3rd ISMFR). https://doi.org/10.1051/e3sconf/202014701002
Fleckenstein LJ, Tierney TW, Fisk JC, Ray AJ (2022) Using alternative low cost-artificial sea salt mixtures for intensive, indoor shrimp (*Litopenaeus vannamei*) production. Aquac Rep 24:101147. https://doi.org/10.1016/j.aqrep.2022.101147
Fossmark RO, Vadstein O, Rosten TW, Bakke I, Košeto D, Bugten AV, Helberg GA, Nesje J, Jørgensen NOG, Raspat G, Azrague K, Østerhus SW, Attramadal KJ (2020) Effects of reduced organic matter loading through membrane filtration on the microbial community dynamics in recirculating aquaculture systems (RAS) with Atlantic salmon parr (*Salmo salar*). Aquaculture 524:735268. https://doi.org/10.1016/j.aquaculture.2020.735268
Galkanda-Arachchige HSC, Roy LA, Davis DA (2020) Evaluation of an alternative salt mixture to culture Pacific white shrimp *(Litopenaeus vannamei*) in inland aquaculture. Aquac Res 51(9):3540-3550. https://doi.org/10.1111/are.14691
Garlock T, Asche F, Anderson J, Ceballos-Concha A, Love DC, Osmundsen TC, Pincinato RBM (2022) Aquaculture: The missing contributor in the food security agenda. Glob Food Sec 32:100620. https://doi.org/10.1016/j.gfs.2022.100620
Gichana ZM, Liti D, Waidbacher H, Zollitsch W, Drexler S, Waikibia J (2018) Waste management in recirculating aquaculture system through bacteria dissimilation and plant assimilation. Aquac Int 26(6):1541-1572. https://doi.org/10.1007/s10499-018-0303-x
GOAL (Global Aquaculture Alliance) (2018) Shrimp Production Review. https://www.globalseafood.org/wp-content/uploads/2017/06/Day1_JimAnderson.pdf. Accessed 18 October 2022
Goldman J (2016) So you want to be a fish farmer? World Aquaclture. www.was.org. Accessed 18 October 2022
Gronau S, Winter E, Grote U (2020) Aquaculture, fish resources and rural livelihoods: a village CGE analysis from Namibia's Zambezi Region. Environ Dev Sustain 22(2):615-642. https://doi.org/10.1007/s10668-018-0212-1
Guevara-Viejó F, Valenzuela-Cobos JD, Grijalva-Endara A, Vicente-Galindo P, Galindo-Villardón P (2022) Data Mining Techniques: New method to identify the effects of aquaculture binder with sardine on diets of juvenile *Litopenaeus vannamei*. Sustainability 14:4203. https://doi.org/ 10.3390/su14074203
Herbeck LS, Unger D, Wu Y, Jennerjahn TC (2013) Effluent, nutrient, and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-reef waters of NE Hainan, tropical China. Cont Shelf Res 57:92-104. https://doi.org/10.1016/j.csr.2012.05.006
Indriastuti CE, Ratnawati B, Budiharto IW (2022) Survival and growth performance the catfish *Clarias gariepinus* in high density nurseries using recirculating aquaculture system (RAS). E3S web of conf. 2nd International Conference on Applied Sciences 2021 (ICAS 2021). https://doi.org/10.1051/e3sconf/202234800013
Kennedy DA, Kurath G, Brito IL, Purcell MK, Read AF, Winton JR, Wargo AR (2016) Potential drivers of virulence evolution in aquaculture. Evol Appl 9(2):344-354. https://doi.org/10.1111/eva.12342
King RK (2001) The presence of bacterial pathogens in biofilms of recirculating aquaculture systems and their response to various sanitizers. Dissertation, Virginia Polytechnic Institute and State University, Virginia. 131 p
Li H, Tian X, Zhao K, Jiang W, Dong S (2019) Effect of *Clostridium butyricum* in different forms on growth performance, disease resistance, expression of genes involved in immune responses and mTOR signaling pathway of *Litopenaeus vannamai*. Fish Shellfish Immunol 87:13-21. https://doi.org/10.1016/j.fsi.2018.12.069
Liltved H, Vogelsang C, Modahl I, Dannevig BH (2006) High resistance of fish pathogenic viruses to UV irradiation and ozonated seawater. Aquacult Eng 34(2):72–82. https://doi.org/10.1016/j.aquaeng.2005.05.002
Lin YF, Jing SR, Lee DY (2003) The potential use of constructed wetlands in a recirculating aquaculture system for shrimp culture. Environ Pollut 123(1):107-113. https://doi.org/10.1016/S0269-7491(02)00338-X

Lorgen-Ritchie M, Clarkson M, Chalmers L, Taylor JF, Migaud H, Martin SA (2021) A temporally dynamic gut microbiome in Atlantic salmon during freshwater recirculating aquaculture system (RAS) production and post-seawater transfer. Front Mar Sci 8:711797. https://doi.org/10.3389/fmars.2021.711797

Losordo TM, Westers H (1994) System carrying capacity and flow estimation. Dev Aquac Fish Sci 27:9-60

Malibari R, Sayegh F, Elazzazy AM, Baeshen MN, Dourou M, Aggelis G (2018) Reuse of shrimp farm wastewater as growth medium for marine microalgae isolated from Red Sea – Jeddah. J Clean Prod 198:160-169. https://doi.org/10.1016/j.jclepro.2018.07.037

Mangott A, Nappi J, Carini ADP, Goncalves P, Hua K, Domingos JA, Thomas T (2020) *Ulva lactuca* as a functional ingredient and water bioremediator positively influences the hepatopancreas and water microbiota in the rearing of *Litopenaeus vannamei*. Algal Res 51:102040. https://doi.org/10.1016/j.algal.2020.102040

Navarro-Peraza RS, Osuna-Ruiz I, Lugo-Sánchez ME, Pacheco-Aguilar R, Ramírez-Suárez JC, Burgos-Hernández A, Martínez-Montaño E, Salazar-Leyva JA (2020) Structural and biological properties of protein hydrolysates from seafood by-products: a review focused on fishery effluents. Food Sci Technol 40(1):1-5. https://doi.org/10.1590/fst.24719

Park, JY, Han KH, Cho JK, Kim KM, Son MH, Park JM, Kang HW (2016) Survival rate and hematological responses with temperature changes of red spotted grouper, *Epinephelus akaara* in South Korea. Dev Reprod 20(2):103. https://doi.org/10.12717/dr.2016.20.2.103

Pumkaew M, Taweephitakthai T, Satanwat P, Yocawibun P, Chumtong P, Pungrasmi W, Powtongsook S (2021) Use of ozone for *Vibrio parahaemolyticus* inactivation alongside nitrification biofilter treatment in shrimp-rearing recirculating aquaculture system. J Water Process Eng 44:102396. https://doi.org/10.1016/j.jwpe.2021.102396

Priyashnatha AKH, Edirisinghe, U (2021) Lessons learnt from the past to mitigate the negative aspects of aquaculture in developing countries. PSAKU Int J Interdiscip Res 10(2). https://dx.doi.org/10.2139/ssrn.3964762

Qin G, Liu CCK, Richman NH, James ETM (2005) Aquaculture wastewater treatment and reuse by wind-driven reverse osmosis membrane technology: a pilot study on Coconut Island, Hawaii. Aquacult Eng 32(3-4):365–378. https://doi.org/10.1016/j.aquaeng.2004.09.002

Qu F, Liang H, Zhou J, Nan J, Shao S, Zhang J, Li G (2014) Ultrafiltration membrane fouling caused by extracellular organic matter (EOM) from *Microcystis aeruginosa*: Effects of membrane pore size and surface hydrophobicity. J Membr Sci 449:58–66. https://doi.org/10.1016/j.memsci.2013.07.070

Rakness KL (2005) Ozone in drinking water treatment: process design, operation and optimization. American Water Works Association, Denver, USA. 305 p

Ray AJ, Drury TH, Cecil A (2017) Comparing clear-water RAS and biofloc systems: Shrimp (*Litopenaeus vannamei*) production, water quality, and biofloc nutritional contributions estimated using stable isotopes. Aquacultural Engineering 77:9-14. https://doi.org/10.1016/j.aquaeng.2017.02.002

Ray AJ, Lotz JM (2017) Shrimp (*Litopenaeus vannamei*) production and stable isotope dynamics in clear-water recirculating aquaculture systems versus biofloc systems. Aquac Res 48(8):4390-4398. https://doi.org/10.1111/are.13262

Rekha NP, Biju IF, Antony J (2018) Recirculating aquaculture systems for *Penaeus vannamei* farming. In: Training manual series. ICAR-Central Institute of Brackishwater Aquaculture. https://courseware.cutm.ac.in/wp-content/uploads/2020/06/Vennamei.pdf. Accessed 18 October 2022

Roques JA, Micolucci F, Hosokawa S, Sundell K, Kindaichi T (2021) Effects of recirculating aquaculture system wastewater on anammox performance and community structure. Processes 9(7):1183. https://doi.org/10.3390/pr9071183

Sharrer MJ, Summerfelt ST (2007) Ozonation followed by ultraviolet irradiation provides effective bacteria inactivation in a freshwater recirculating system. Aquac Eng 37(2):180-191. https://doi.org/10.1016/j.aquaeng.2007.05.001

Suantika G, Situmorang ML, Kurniawan JB, Pratiwi SA, Aditiawati P, Astuti DI, Azizah FFN, Djohan YA, Zuhri U, Simatupang TM (2018a) Development of a zero water discharge (ZWD)-Recirculating aquaculture system (RAS) hybrid system for super intensive white shrimp (*Litopenaeus vannamei*) culture under low salinity conditions and its industrial trial in commercial shrimp urban farming in Gresik, East Java, Indonesia. Aquacult Eng 82:12-24. https://doi.org/10.1016/j.aquaeng.2018.04.002

Suantika G, Situmorang ML, Nurfathurahmi A, Taufik I, Aditiawati P, Yusuf N, Aulia R (2018b) Application of indoor recirculating aquaculture system for white shrimp (*Litopenaeus vannamei*) growout super-intensive culture at low salinity condition. J Aquac Res Develop 9(4):1000530. http://dx.doi.org/10.4172/2155-9546.1000530

Suantika G, Situmorang ML, Saputra FI, Putri SLE, Putri SP, Aditiawati P, Fukusaki E (2020) Metabolite profiling of whiteleg shrimp *Litopenaeus vannamei* from super-intensive culture in closed aquaculture systems: a recirculating aquaculture system and a hybrid zero water discharge-recirculating aquaculture system. Metabolomics 16:49. https://doi.org/10.1007/s11306-020-01675-1

Summerfelt ST, Sharrer MJ, Hollis J, Gleason LE, Summerfelt SR (2004) Dissolved ozone destruction using ultraviolet irradiation in a recirculating salmonid culture system. Aquacult Eng 32(1):209-223. https://doi.org/10.1016/j.aquaeng.2004.06.004

Tango MS, Gagnon GA (2003) Impact of ozonation on water quality in marine recirculation systems. Aquacult Eng 29(3-4):125–137. https://doi.org/10.1016/S0144-8609(03)00061-X

Teitge F, Peppler C, Steinhagen D, Jung-Schroers V (2020) Water disinfection by ozonation has advantages over UV irradiation in a brackish water recirculation aquaculture system for Pacific white shrimp (*Litopenaeus vannamei*). J Fish Dis 43(10):1259-1285. https://doi.org/10.1111/jfd.13238

Tierney TW, Ray AJ (2018) Comparing biofloc, clear-water, and hybrid nursery systems (Part I): Shrimp (*Litopenaeus vannamei*) production water quality, and stable isotope dynamics. Aquacult Eng 82:73-79. https://doi.org/10.1016/j.aquaeng.2018.06.002

Valenzuela Cobos J, Vargas Farías C (2019) Study about the use of aquaculture binder with tuna attractant in the feeding of white shrimp (*Litopenaeus vannamei*). Rev Mex Ing Quim 19(1):355-361. https://doi.org/10.24275/rmiq/Bio615

Wang Y, Chi L, Liu Q, Xiao Y, Ma D, Xiao Z, Xu S, Li J (2019) Effects of stocking density on the growth and immunity of Atlantic salmon salmo salar reared in recirculating aquaculture system (RAS). J Oceanol 37(1):350-360. https://doi.org/10.1007/s00343-019-7350-7

Wardhana RA, Yuniarsih E, Adhitya I (2021) Sustainable aquaculture development in Indonesia. https://repository.seafdec.org.ph/handle/10862/6251. Accessed 11 November 2022

Weirich CR, Browdy CL, Bratvold D, McAbee BJ, Stokes AD (2002) Preliminary characterization of a prototype minimal exchange super-intensive shrimp production system. Proceedings of the 4th International Conference Recirculating Aquaculture, Virginia

Tech University, Blacksburg, VA. 255-270
Xiao R, Wei Y, An D, Li D, Ta X, Wu Y, Ren Q (2019) A review on the research status and development trend of equipment in water treatment processes of recirculating aquaculture systems. Rev Aquac 11(3):863-895. https://doi.org/10.1111/raq.12270
Yang JN, Qingyuan Z, Yuchao B, Xu (2010) Construction technology on RAS for shrimp culture. TCSAE 26(8):136-140. http://dx.doi.org/10.3969/j.issn.1002-6819.2010.08.023
Zhang SY, Li G, Wu HB, Liu, XG, Yao YH, Tao L, Liu H (2011) An integrated recirculating aquaculture system (RAS) for land-based fish farming: The effects on water quality and fish production. Aquacult Eng 45(3):93-102. https://doi.org/10.1016/j.aquaeng.2011.08.001
Zhong F, Liang W, Yu T, Cheng SP, He F, Wu ZB (2011) Removal efficiency and balance of nitrogen in recirculating aquaculture system integrated with constructed wetlands. J Environ Sci Health A 46(7):789-794. https://doi.org/10.1080/10934529.2011.571974
Zulkarnain R, Adiyana K, Waryanto, Nugroho H, Thesiana L, Supriyono E (2020) Selection of intensive shrimp farming technology for small farmers with analytical hierarchy process: a case for whiteleg shrimp (*Litopenaeus vannamei*). IOP Conf. Ser.: Earth Environ Sci 404 012017:1-8. doi:10.1088/1755-1315/404/1/012017