Land-Based Intensive Aquaculture Systems 10

Xiang-Li Tian and Shuang-Lin Dong

Aquaculture production in China mainly derives from ponds, nearshore areas, lakes, reservoirs, and other waters in various forms. Generally, the intensification degree for these types of aquacultures is relatively low, and most of them are extensive or semi-intensive systems. To improve culture yield and economic benefits, aquaculture industry around the world has shown a tendency of intensification in recent years, i.e., increasing the proportion of fed species production, the adoption of intensive aquaculture systems (cage, pen, raceway, indoor facilities), and application of oxygenators. With the intensification of pond farming, increased freshwater consumption and pollutant discharge have affected the sustainable development of pond farming. Therefore, some land-based intensive aquaculture models have been adopted to solve these problems. This chapter will introduce the principles of land-based intensive aquaculture systems, such as recirculating aquaculture systems, solar recirculating aquaculture systems, raceway aquaculture systems, and biofloc-based aquaculture systems.

10.1 Recirculating Aquaculture Systems

Recirculating aquaculture systems (RAS), also called industrial aquaculture systems in China, are tank-based closed-loop aquaculture systems in which aquatic organisms can be cultured at high density under controlled environmental conditions. Conventional RASs are based on the function of microbial nitrification to retain and treat the water within the system, modern RASs are beginning to pay

X.-L. Tian · S.-L. Dong (✉)
Laboratory of Aquaculture Ecology, College of Fisheries, Ocean University of China, Qingdao, China
e-mail: xianglitian@ouc.edu.cn; dongsl@ouc.edu.cn

S.-L. Dong et al. (eds.), *Aquaculture Ecology*,
https://doi.org/10.1007/978-981-19-5486-3_10

attention to microbial denitrification, and the role of plant photosynthesis is in removing dissolved nutrients from water.

10.1.1 Principles of Conventional Recirculating Aquaculture Systems

The 'wastewater' or 'tailwater' discharged from the RAS is slightly polluted, which can be treated and then recycled. The wastewater is treated with various physical, chemical, and biological methods. Generally, the essential treating process includes mechanical filtration, biofiltration, disinfection, temperature regulation, oxygen supply, etc. Normal components of RAS used for fish culture are as follows: a culture tank, sedimentation tank, physical clarification units, biofiltration units, and disinfection units (Fig. 10.1).

After aeration, sedimentation, filtration, and disinfection, the water discharged from the RAS culture tank is temperature-regulated, oxygenated, and supplemented with the appropriate amount of fresh water (1–10%, replenishing the lost or evaporated water in the system) according to the physiological requirements of different culture species and their growth stages, and then flows back into the culture tanks for recycling use. Generally, less freshwater is used by RAS, 3000–45,000 L/kg of fish in a typical culture system. Some RAS with artificial seawater even uses as little as 16 L/kg of freshwater (Klinger and Naylor 2012). This system is also equipped with water quality monitoring, flow rate control, automatic feeding, waste disposal, and other devices, and is automatically monitored by the central control room.

Compared with the traditional outdoor pond aquaculture systems, RASs possess the following obvious advantages: (1) Conserve heat and water through water treatment by biofilters. (2) Less pollutants are discharged and environmentally friendly. (3) Have predictable harvesting schedules according to market demands all year round. (4) Allow effective economies of scale, resulting in the highest

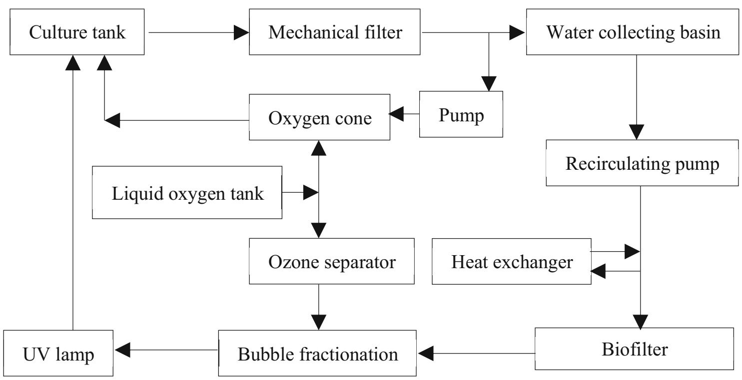


Fig. 10.1 A general diagram of water treatment process in a typical recirculating aquaculture system.

productivity. (5) Location can be more freely decided, e.g., the location can be close to the marketplace to reduce logistics costs. (6) Operation can be conducted according to specifications; therefore, their products are traceable, diseases are preventable, and food safety is guaranteed. (7) Employ a greater range of workers, such as the elderly and women due to high mechanization. (8) Biosafety is highly secured due to good containment. Some species with high biosafety requirements, such as transgenic fish, can be cultured safely.

The product quality between RAS and outdoor mariculture is also different apparently. For example, the tiger puffer fish *Takifugu rubripes* grown in RAS have less damage in caudal fin; their products have minimal risk of poisoning, have higher score in taste tests compared to those grown in net cage (Takeuchi 2017). In addition, marine RAS are not affected by red tides and epidemic pathogens directly, making RAS farming safer.

In recent years, great progress has been made in the research and development of genetic engineering technology for aquatic animals, and transgenic marine Atlantic salmon and transgenic freshwater Nile tilapia have been successful, and their growth rates and food utilization have improved about one time compared with the original species. RAS is the most ideal facility to guarantee the safety of transgenic animal farming, and in this regard, RAS also has a broad prospect.

In early or conventional RAS, all parts of the system are basically under aerobic conditions, especially for the biofilter, which is generally always under aerated conditions. Therefore, anaerobic denitrification is inhibited and can be ignored in the system. The aeration allows the microorganisms on the biofilter to full contact with the water, and the efficient nitrification oxidizes NH_4^+ to NO_3^-. At the same time, the pH of the aqueous environment decreases.

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$$

$$NO_2^- + 0.5O_2 \rightarrow NO_3^-$$

However, the total amount of dissolved inorganic nitrogen in the RAS does not reduce actually, and the microorganisms in the biofilter only convert NH_4^+, which is toxic to farmed animals, to NO_3^-. Although NO_3^- is not highly toxic to fish, its excessive accumulation in the RAS can also affect the growth and immunity of farmed fish and, in severe cases, endanger their survival (Freitag et al. 2015). Also, once a zero discharge RAS operated in long-term discharges, the total inorganic nitrogen concentration in the effluent will still exceed the corresponding limits of discharge standards.

Ammonia in the water exists in two forms, un-ionic ammonia (UIA, NH_3) and ionized NH_4^+, with the relative concentration primarily a function of pH and temperature. An increase in pH or temperature increases the proportion of UIA. UIA is highly toxic to fish at low concentrations. NH_4^+ and NH_3 in RAS water constitute the following equilibrium:

$$NH_4^+ + H_2O \leftrightarrow NH_3 + H_3O^+$$

Once the pH of the water increases, the proportion of UIA will increase as well. Some zero discharge RAS often reduce the pH of the water to 6.5 or less to ensure the safety of farmed animals. The acidic water environment is unfavorable to the growth and molting of aquatic animals. The high concentration of total inorganic nitrogen and the acidic water environment are the main defects of conventional RAS.

10.1.2 Denitrification in Modern Recirculating Aquaculture Systems

During the aerobic biofiltration process, ammonia is nitrified to the form of less toxic nitrate, which accumulates in the water. The water exchange rates of conventional RAS are generally 0.1–1.0 m^3/kg feed (Martins et al. 2010). To overcome the shortcomings of high total inorganic nitrogen accumulation in conventional RAS, modern RASs have introduced microbial denitrification unit into the systems to reduce the concentration of NO_3^- in the systems (Fig. 10.2). The denitrification unit in modern RAS converts NO_3^- and NO_2^- to N_2, which can eventually escape from the RAS system, under anaerobic conditions by the following reactions:

$$C_6H_{12}O_6 + 12NO_3^- \rightarrow 12NO_2^- + 6CO_2 + 6H_2O$$

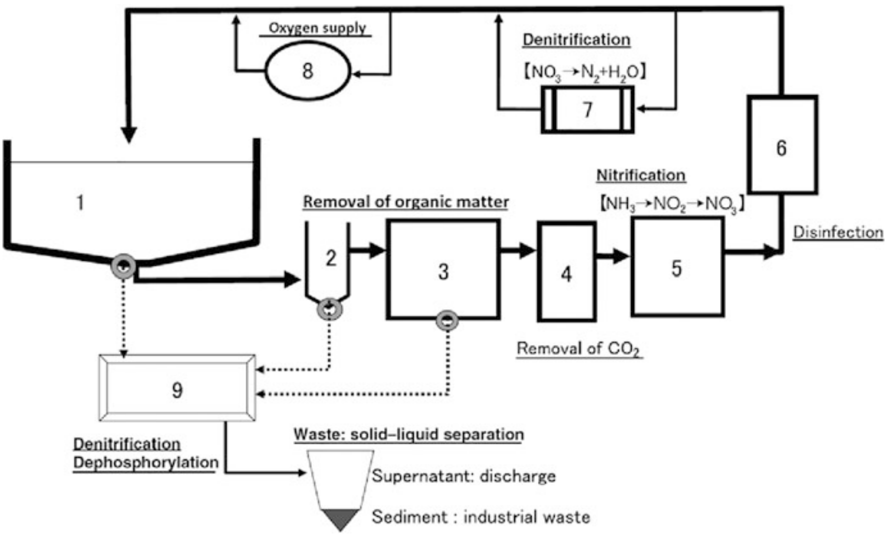


Fig. 10.2 Schematic diagram of equipments and its function in RAS (from Yamamoto 2017). (1) Rearing tank; (2) sedimentation tank; (3) physical filter unit; (4) degasifier; (5) biofilter unit; (6) disinfection unit; (7) denitrification unit; (8) oxygen supply unit; (9) waste treatment unit.

$$C_6H_{12}O_6 + 8NO_2^- \rightarrow 4N_2 + 2CO_2 + 4CO_3^{2-} + 6H_2O$$

Traditional denitrification theory suggests that denitrifying enzymes are active only under anoxic or partly anaerobic conditions. Robertson and Kuene (1984) reported the existence of aerobic denitrifying bacteria and aerobic denitrifying enzyme systems, which provides a new way for the removal of nitrate in aquaculture systems under aerobic conditions. Recent studies have shown that the reactor of heterotrophic nitrifying-aerobic denitrifying bacteria can directly use the nitrate nitrogen and nitrite nitrogen produced by the nitrification process as substrates for aerobic denitrification, which greatly reduces the operating costs and operational difficulties (Huang et al. 2018).

The main factors affecting aerobic denitrification are carbon source, dissolved oxygen, and the ratio of carbon to nitrogen (C:N). As carbon sources for denitrification of Siberian sturgeon (*Acipenser baeri*) aquaculture system, methanol, acetic acid, glucose, and hydrolyzed starch are effective in reducing nitrate-nitrogen concentrations from 11–57 mg/L to undetectable levels (Hamlin et al. 2008). In a CRAS for rainbow trout with a rotating disk filter serving as biofilter, water quality is maintained by the addition of hydrolyzed corn starch with organic C:N of 1.6:1 to promote the growth of aerobic denitrifying bacteria. During the culture period of 118 d, nitrate nitrogen decreased from 120 to 10 mg/L and stabilized thereafter (Kaiser and Schmitz 1988).

Aerobic denitrifying bacteria have a dissolved oxygen threshold, above or below which the rate of aerobic denitrification decreases. For example, the dissolved oxygen threshold of *Citrobacter diversus* is 5 mg/L. Aerobic denitrifying bacteria require a certain C:N ratio in water, and the optimal C:N ratio required by various aerobic denitrifying bacteria varies as well.

Compared with the aerobic nitrification process in RAS, the aerobic denitrification process has the advantages of small footprint and the ability to achieve simultaneous nitrification and denitrification. As an example, in a 600 MT/year Nile tilapia RAS farm integrating with a denitrification reactor using internal carbon source in the Netherlands, the water exchange rate is as low as 30 L/kg feed, corresponding to 99% recirculation (Martins et al. 2009). The requirements for water, heat, and bicarbonate are lower in the denitrification RAS than in the conventional RAS for tilapia farming (Eding 2009). The denitrification RAS has somewhat higher cost of oxygen, electricity, and labor, but the actual production costs for unit product are 10% lower than for the conventional RAS. Waste discharge is significantly reduced by the denitrification RAS compared with the conventional RAS (Eding 2009).

10.1.3 Commercial Application of Recirculating Aquaculture Systems

The concept of closed recirculating aquaculture system (CRAS) was first proposed by a Japanese scientist Saeki (1958), and by the 1970s, experimental research on

RAS began in Europe and the United States. The countries that started the commercial application of RAS earlier include the Netherlands and Denmark, etc. In 2018, China's industrial aquaculture (including RAS and flow-through systems) production was 469,000 t, of which 54.5% was from mariculture systems.

Most existing commercial RASs produce high-price species, including rainbow trout, salmon, tilapia, turbot, eel, African catfish, striped bass, sturgeon, arctic char, halibut, sea bass, whiteleg shrimp, etc. The most of RASs have been developed for small-scale operations ($<$50 t of output per year), and there are few large-scale ones ($>$50 t of output per year). High start-up costs combined with uncertain profitability have discouraged investments (Klinger and Naylor 2012).

Water quality of RAS relies entirely on water treatment facilities and dissolved oxygen supplementation. It is also necessary for RAS to regulate and control the temperature and lighting. Thus, RAS consumes much more operational energy than most other types of aquaculture systems. The total energy consumption per unit product for pond, industrial aquaculture (including RAS and flow-through systems), and net cage culture in China are 0.37, 8.66, and 3.16 kWh/kg (Xu et al. 2011). Klinger and Naylor (2012) also summarized that the total energy consumptions (including feed) of carnivorous-finfish RAS facilities, net pen, and flow-through systems are 16–98, 7.4, and 27.2 kWh/kg product. More energy consumption means more indirect CO_2 emission (1 kWh/kg = 0.997 CO_2) and high carbon footprint.

Since energy prices are relatively lower in developed countries and labor costs are extremely high, it is logical that RAS, which uses less labor and consumes more electricity, was invented in developed countries. However, compared with developed countries, China's relatively higher energy prices and still low labor costs make RAS products uncompetitive in many cases. However, due to the incentive policies of China government, the industrial farming production in China increases by 8.0% per year in the past decade. In fact, the sustainability of RAS development is not high in China (see Chap. 14). RAS products can be competitive only if the effluent from pond farming and groundwater extraction for aquaculture are strictly supervised in near future.

The energy consumption of RAS farming tiger puffer (*Takifugu rubripes*) in Japan accounts for 39.3% of the total costs (Takeuchi 2017). The energy consumption for flatfish farming in Europe accounts for 11%, while the corresponding cost in China accounts for 28% (Ying Liu, private communication). Therefore, reducing energy consumption is still an important task for the development of RAS in China. RAS can save energy with the help of other energy sources, such as farming warm water species with warm water drainage from power plants, farming cold-water fish with cold water drainage of liquefied natural gas (LNG) facilities, or farming aquatic organisms by artesian water of high-water level of water sources, etc.

Recently, the concept of Closed Ecological Recirculating Aquaculture Systems (CERAS) has been proposed and experimental studies of CERAS with phytoplankton, zooplankton, tilapia, and biofilters as the main components have been conducted (Takeuchi 2017). These researches are of great importance for future deep space exploration and construction of artificial floating islands at sea.

Food production systems without photosynthesis are usually not high in ecological efficiency because of the large amount of artificial energy, and material inputs are required to run such systems. The following will introduce the energy saving and emission reduction effects of integrating photosynthesis into a CRAS to build a solar recirculating aquaculture system.

10.2 Solar Recirculating Aquaculture Systems

The main problems of conventional RASs based on nitrification are high energy consumption and inorganic nitrogen accumulation, and RASs with denitrification function still have the problem of high energy consumption. The designers of RASs always try to achieve full artificial control of the aquaculture environment, ignoring or excluding the roles of ecosystem services, especially the photosynthesis, in regulating water quality. In this section, we introduce the solar recirculating aquaculture system (SRAS) that implants aquatic plants (submerged macrophytes, floating or emergent plant, phytoplankton) into RAS, including aquaponic system (APS) based on floating or emergent plant, submerged plant-based SRAS, and phytoplankton-based SRAS.

10.2.1 Aquaponic Systems

10.2.1.1 Principles and Advantages of Aquaponic Systems

Conventional RAS is one of the most productive aquaculture systems, but its drawback is that it eventually discharges wastewater. Hydroponics is one of the most productive agricultural production systems, but it requires additional nutrients input. Conventional RAS and hydroponics are somewhat complementary in terms of the nutrient balance of the system. Aquaponic system (APS) is a combination of conventional RAS and hydroponics, implanting emergent plants or floating plants into a recirculating aquaculture system. However, only the systems in which more than 50% of the nutrients absorbed by the 'vegetables' in the system can be called APS (Lennard and Goddek 2019).

APS takes advantage of the mutually beneficial effects of fish and plants fully. The implanted plants absorb and remove excess nutrients from the aquaculture environment, achieving the goals of water purification, effluent reduction, and economic benefit increment. The production of fish and aquatic plant in an ideal APS can be comparable to the number of fish produced by a RAS plus the number of vegetables produced by another hydroponics (Lennard 2005).

The basic units of APS consist of fish culture ponds or tanks, settling pond or sedimenter, biofilter, hydroponic component, and sump (Fig. 10.3). The hydroponic unit consists of a pond, a substrate of gravel and sand (or porous plastic films), and plants. The residual feeds and fecal particles produced by fish culture unit can be removed by settling tanks or mechanical filters; ammonia produced by the cultured

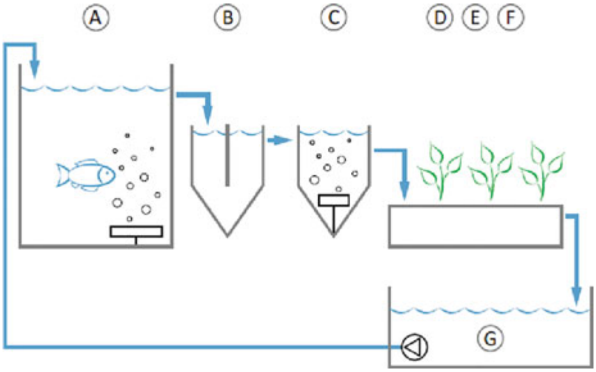


Fig. 10.3 Schematic diagram of an aquaponic system (from Palm et al. 2019). (**a**) Fish tank and aeration, (**b**) Sedimenter, (**c**) Biofilter with substrates and aeration, (**d**)–(**f**) Hydroponic unit, (**g**) Sump with pump.

fish is converted to nitrate by the biofilter and later reabsorbed and used by the cultivated plants together with phosphate.

The APS should be designed as the following: (1) The system should turn the waste derived from cultured fish into edible or commercial plants. (2) The system should improve the utilization of inorganic nutrients in the water derived from cultured fish by hydroponic plants as much as possible to reduce the direct impact of the system on the surrounding environment. (3) The system uses techniques that do not impede the use of water and nutrients by the cultured fish and cultivated plants. For example, the use of earthen ponds is not recommended, but rather plastic, fiber reinforced plastic, or cement ponds, because the seepage of water and the adsorption or release of nutrients from earthen ponds can interfere with the utilization of water and nutrients by fish and plants. (4) The wastewater and nutrients should not discharge outside the system, otherwise. If the wastewater and nutrients have to flow out of the system, these effluents and nutrients should also be reused by external plants to produce edible or commercial bio-products to avoid a wider impact on the environment. (5) APS should be built in environmentally controlled structures (e.g., greenhouses) to obtain optimal fish and plants production (Lennard and Goddek 2019).

Only 25–35% of the nutrients in the feed are used by RAS-farmed fish, the rest needs to be treated or will be discharged to the surrounding environment. Nitrate nitrogen and phosphate removal rates of RASs range from 9 to 93% and 0 to 53%, respectively (Endut et al. 2010; Graber and Junge 2009; Lennard and Leonard 2006). The water recycling rates of APS are 90% greater than standard RAS (Lennard 2005). Water recycling rates as high as 98% have been reported in some systems, translating to water use of about 320 L water/kg fish produced (Al-Hafedh et al. 2008). APS with better design and operation requires only 1.5% of water replenishment per day (to supplement for evaporative losses), and water consumption is only 1% of that of earthen pond culture. In addition, the construction of APS does not require consideration of the types of soil, which makes the site selection for construction more flexible and allows the use of wasteland or marginal land.

10.2.1.2 Management and Structural Optimization of Aquaponic Systems

For fully cycled APS, the control and regulation of the physicochemical parameters of the water quality should generally be based on the requirements of the cultured fish, since fish are usually more demanding on the environment than hydroponically grown plants and microorganisms in biofilters. However, the pH requirements of cultured fish, cultivated plants, and microorganisms in biofilters vary widely, and much work remains to be conducted in this regard, both in terms of feed composition and engineering techniques (Tyson et al. 2011; Endut et al. 2010). Considering hydroponic plants alone, a pH of 4.5–6.0 is optimal, but fish require a pH of 7.0–8.0. For this reason, additive buffer technology and a decoupled aquaponic system (DAPS) have been developed. Since calcium and potassium ions in fish feeds are insufficient for aquaponic plants, and microorganisms in the biofilter lower the pH of the water, buffers containing carbonic or bicarbonic acid or hydroxylated calcium or potassium compounds can be added in different units to meet the specific pH requirements of fish and plants. Water flowing through the hydroponic units in a DAPS no longer returns to the fish culture units, so some substances beneficial to plant or microorganisms can be added to the water after it flows out of the fish culture units and before it flows into the hydroponic unit and the biofilter (Goddek et al. 2019). However, the narrow definition of aquaponics given by some does not include such DAPS (Lennard and Goddek 2019).

APS yield, fish metabolic waste removal rates, and water recycling rate are related to plant species, water exchange rate, and biomass ratio of fish to plant. The optimal biomass ratio of fish to plants in APS is theoretically the cultivated plants that can just fully absorb the metabolic waste inflow from the previous unit (e.g., biofilter). When feeding tilapia with feeds containing 32% protein, 1 m^2 of cultivated plants can treat the wastewater from 60–100 g of feed input per day, so Rakocy et al. (2006) set the feeding rate at 60–100 $g/(m^2 \cdot d)$. The feeding rate is 15–24 $g/(m^2 \cdot d)$ for the APS of African catfish and *Ipomoea aquatica*. It can be seen that the feeding rates are species-specific.

Although integration of agriculture and aquaculture has a long history in China, Southeast Asia, and South America, modern APS originated in the United States in the 1970s, and James Rakocy and his team did much of the groundwork for the development of APS in the early 1980s (Goddek et al. 2019). There are more than 1500 aquaponic operations in the United States and an even greater number in Australia (Rakocy et al. 2010). This technology is used currently by commercial, research, educational, and not-for-profit organizations, as well as by private hobbyists. Most operations are small in scale (<50 t per year) (Klinger and Naylor 2012). Large-scale commercially operated APSs are mostly found in arid regions such as the Arabian Peninsula, Australia, and sub-Saharan Africa (Goddek et al. 2019). The most popular species combination in APS is tilapia and lettuce.

Despite the many advantages of APS, there are not many cases of large-scale commercial operation in regions other than arid areas due to economic constraints and technical obstacles. APS requires relatively large amounts of land and complex equipment, making land, construction, and operation costs high. To reduce construction and operation costs, many APSs now eliminate the water disinfection process. For soilless cultivation traditions in agriculture, water disinfection usually is a routine technique. Disinfection techniques are also commonly used in some high-density RAS systems to prevent disease in farmed animals. However, both decomposition of culture waste and nutrient uptake by plant roots require the involvement of microorganisms, thus, water disinfection is a double-edged sword. Considering that the gravel and facilities in the hydroponic unit already have a large surface area for microbial attachment, some APSs simply eliminate the biofilter unit as well. In the past, small-scale APS focused more on the utilization of input materials and the impact on the environment; however, a tradeoff between operating costs, metabolic waste utilization efficiency, and water recycling rate is an important consideration for every investor and operator of a large-scale APS (Goddek et al. 2019; Klinger and Naylor 2012).

Although APS has developed rapidly in recent decades, there are still many problems that need to be resolved furtherly. Compared with pond farming, APS is an aquaculture system with a relatively high carbon footprint, and there is still a lot of work needed on how to effectively use green energy to drive APS production. In addition, there are additional concerns about food safety and consumer acceptance of APS products for some Westerners (Goddek et al. 2019; Klinger and Naylor 2012). It is evident that there is still much work to be done on popularization of science, legislation, and product safety certification of APS. More about APS in detail can be read in *Aquaponics Food Production Systems* (Goddek et al. 2019).

10.2.2 Solar Recirculating Aquaculture Systems Based on Submerged Plants

10.2.2.1 Structure of SRAS Based on Submerged Plant

A submerged plant-based SRAS is formed by introducing submerged plants into RAS and allowing sunlight to be accessible to the photosynthetic unit (Fig. 10.4).

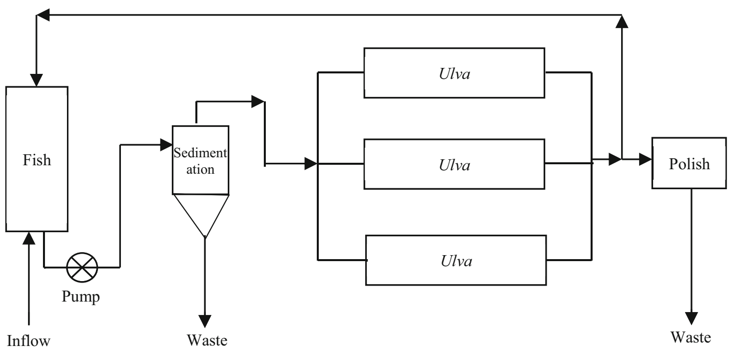


Fig. 10.4 Schematic diagram of fishpond-seaweed biofilter system (from Krom et al. 1995). Arrows indicate the direction of water flow.

The aquatic plants carry out the following photosynthetic reactions under the sunlight:

$$106CO_2 + 90H_2O + 16NO_3^- + 1PO_4^{3-} + \text{mineral elements} = 3258\text{ g protoplasm} + 154O_2.$$

The aquatic plants absorb CO_2, NO_3^-, and PO_4^{3-} from the water, and release dissolved O_2 into the water, which purifies the water. If the aquatic plant is an economic plant, it will gain additional income from this new product. Thus, the implantation of the plants has the effect of eliminating pollutants, increasing dissolved oxygen and the income from new products.

Submerged plant implantation is divided into two categories: in situ and ex situ implantation. In situ implantation is the combination of photosynthetic unit and fish farming unit, i.e., polyculture of aquatic animal and plant in the same unit. The system shown in Fig. 10.3 is a SRAS with ex situ implantation, except for emergent aquatic plant. Some freshwater RASs discharge the effluent into an artificial wetland and use the plants in the wetland to absorb inorganic nutrients from the water. The principle of this type of system is similar to SRAS, except that the oxygen released by photosynthesis of the plants is not utilized by the RAS system.

10.2.2.2 Light and Temperature Control of SRAS

The sunlight is not necessary for RAS using microbial filters. In order to maintain the temperature in workshop, this type of culture system is usually equipped with thermal insulation facilities, and the roof of the workshop is mostly opaque or with low transparency. If the SRAS is treated in situ or if the photosynthesis unit is placed in the same workshop with the main culture unit, it is necessary to consider the light-transmission treatment of the roof of the culture workshop and to regulate the temperature in the culture workshop. Generally, the light compensation point of macroalgae is mostly above 2000 Lx; therefore, the plants in SRAS need a transparent roof to obtain sufficient light for photosynthesis. However, too much light may inhibit the normal growth of some cultured fish. Therefore, the control of light intensity should tradeoff between the photosynthetic needs of aquatic plants and the growth of cultured animals.

To control the light intensity in the workshop, various methods can be selected, such as shading the roof with materials suitable for light transmission or coverages of sunlight shading net with different light transmission, etc.

Temperature control of SRAS includes lowering temperature in summer and heating in winter. Indoor cooling system can use ventilation cooling, shading cooling, pad-fan cooling, spray cooling, etc. In addition, groundwater can be used for cooling as well, such as technique of Water Supply Heat Pump. Indoor winter heating technology, in addition to insulation devices, includes boilers, the warm water discharged from power plant, etc.

10.2.2.3 Ratio of Fish to Algae in SRAS Systems

The appropriate ratio of cultured animals to macroalgae or aquatic plants is one of the key issues that must be considered for in situ SRAS. Wang et al. (2016) investigated industrial in situ polyculture of *Gracilaria lichevoides* with hybrid grouper (*Epinephe lusfuscoguttatus* ♀ × *E. luslanceolatus* ♂) in a flow-through aquaculture system. The daily water exchange rate is 400%, and stocking rate of the fish is 18.3 ind./m^2 or 0.38 kg/m^2. All polyculture treatments are better than the grouper monoculture in terms of water quality and grouper growth indexes during the period of 2 months. The stocking density of seaweed has a significant influence on the growth performance of both fish and seaweed. In the experimental density range, the water quality tends to be better with the increase of seaweed stocking density. The seaweed yield is the highest at a stocking density of 500 g/m^2. The growth rates of fish in the polyculture treatments are significantly higher and the food conversion rate is significantly lower than those of grouper monoculture. The best growth performance is exhibited in fish polyculture with seaweed of 500 g/m^2.

10.2.2.4 Comparison of Polyculture Models of Grouper and Aquatic Plants

Both seaweeds and higher aquatic plants, as primary producers, can absorb inorganic nutrients from water and improve water quality, and have been widely used in water environment restoration and integrated aquaculture. *G. lichevoides* grows well in light of 120–300 μE/(m^2·s), temperature of 24–36 °C, and salinity of 20–35 ppt (Huang et al. 2013). Inorganic nitrogen and phosphorus concentrations are reduced by 36.8% and 15.2%, respectively in the polyculture ponds of *G. lichevoides* and *Epinephelus awoara* compared with the grouper monoculture (Xu et al. 2007b). *G. lichevoides* can also reduce significantly the inorganic nitrogen and phosphorus concentrations of fish culture area with net cage (Tang et al. 2005).

Caulerpa lentillifera (Chlorophyta) is an edible and high economic value seaweed, native to Southeast Asia, Japan, tropical and subtropical waters of Oceania (Jiang et al. 2014a). In recent years, it has been successfully cultured on a large scale in China (Jiang et al. 2014b; Tan et al. 2014). *Sesuvium portulacastrum* is a herbaceous plant and can grow in non-saline or saline environments. At its stable growth phase, it can remove ammonia and nitrite up to 74%–91% and 93%–98% respectively from mariculture ecosystems, and effectively improves water quality of the culture environment (Dou et al. 2011). However, compared with the in situ polyculture with seaweeds, the use of biofloating rafts has some limitations. For example, it cannot effectively absorb CO_2 in the water and cannot release oxygen into the water.

As compared to the monoculture system of hybrid grouper, water quality indexes in polyculture systems with *G. lichevoides* (submerged, FA, 500 g/m^2), *C. lentillifera* (submerged, FB, 500 g/m^2), and *S. portulacastrum* (emerged plant, FC, 2000 g/m^2) are improved totally (Wang 2016). Water quality of polyculture system of grouper with *S. portulacastrum* is the best, and concentrations of NH_4^+-N, NO_2^--N, PO_4^{3-}-P,

Table 10.1 Water quality and growth of aquatic plants for different treatments (from Wang 2016)

Parameters	Treatments			
	F	FA	FB	FC
NH_4^+-N (μg/L)	271.15 ± 13.14[a]	230.42 ± 11.62[b]	214.95 ± 10.20[b]	220.15 ± 13.04[b]
NO_2^--N (μg/L)	50.33 ± 2.19[a]	43.65 ± 1.96[b]	45.19 ± 2.02[b]	42.73 ± 2.17[b]
PO_4^{3-}-P (μg/L)	73.08 ± 1.99[a]	68.17 ± 1.49[b]	69.12 ± 1.28[b]	63.70 ± 2.05[c]
TN (mg/L)	2.10 ± 0.11[a]	1.90 ± 0.06[b]	1.94 ± 0.09[ab]	1.83 ± 0.12[b]
TP (μg/L)	182.04 ± 8.60[a]	174.04 ± 8.59[ab]	173.54 ± 13.68[ab]	157.50 ± 12.21[b]
COD (mg/L)	2.92 ± 0.12[a]	2.36 ± 0.14[b]	2.64 ± 0.40[ab]	2.05 ± 0.13[c]
Suspended solids (mg/L)	7.75 ± 0.32[a]	5.17 ± 0.13[b]	5.20 ± 0.26[b]	4.58 ± 0.12[c]
SGR of plants (%/d)	–	1.08 ± 0.04[a]	1.63 ± 0.08[b]	2.49 ± 0.09[c]

Note: *A Gracilaria lichevoides*, *B Caulerpa lentillifera*, *C Sesuvium portulacastrum*, *F* grouper. Stocking densities of plants in FA, FB, and FC are 500, 500, and 2000 g/m^2, respectively

Table 10.2 Growth performance of the grouper in different treatments (from Wang 2016)

Treatments	Initial weight (g)	Final weight (g)	Weight gain rate (%)	*SGR* (%/d)	Food conversion rate
F	374.5 ± 6.71	566.1 ± 10.71[a]	51.15 ± 2.64[a]	0.69 ± 0.03[a]	1.11 ± 0.02[a]
FA	374.5 ± 6.71	594.6 ± 9.71[b]	58.76 ± 1.79[b]	0.77 ± 0.02[b]	1.07 ± 0.01[b]
FB	374.5 ± 6.71	602.2 ± 11.37[bc]	60.80 ± 2.12[bc]	0.79 ± 0.03[bc]	1.05 ± 0.006[bc]
FC	374.5 ± 6.71	613.8 ± 8.53[c]	63.90 ± 2.12[c]	0.82 ± 0.02[c]	1.02 ± 0.004[c]

COD and suspended solids are significantly lower than those of other treatments (Table 10.1).

Among three polyculture systems, the *SGR* of *S. portulacastrum* is the highest with 2.49 ± 0.09%/d, which is significantly higher than other two plants (Table 10.1). The *SGRs* of the grouper range from 0.69 to 0.82%/d, with the highest in the polyculture system with *S. portulacastrum*, significantly higher than those in polyculture system with *G. lichevoides* and grouper monoculture. The food conversion rates of the grouper range from 1.02 to 1.11, with the highest in the polyculture system with *S. portulacastrum*, significantly higher than those in polyculture system with *G. lichevoides* and grouper monoculture (Table 10.2).

Overall, the specific growth rates of the grouper in polyculture are higher than that in monoculture, and food conversion rates are lower. Among polyculture systems, the specific growth rate of grouper in polyculture system with *S. portulacastrum* (0.82%/d) is higher than those with *G. lichevoides* (0.77%/d) and *C. lentillifera* (0.79%/d). The food conversion rate of grouper in this system is the lowest (1.02) among them.

In terms of the added economic value of plants, *C. lentillifera* is much higher than other two aquatic plants; However, the effect of water quality improvement by *S. portulacastrum* is somewhat better than that by *C. lentillifera* (Jiang et al. 2014a). In addition, the culture process of *C. lentillifera* is more tedious than other two.

10.2.2.5 Research and Development of SRAS in Other Countries

There have been many researches and practices of using macroalgae and other plants as biofilters for water purification in aquaculture in other countries. Most of SRASs use ex situ culture macrophytes to treat the discharge water from culture units. The integrated culture system of *Sparus aurata* and *Ulva lactuca* biofilter designed by Krom et al. (1995) can remove 9–20% of N from the system (Fig. 10.3). Another integrated culture system consisting of abalone (*Haliotis discus hannai*) culture pond, sea bream (*Sparus aurata*) culture pond, and *Ulva lactuca* biofilter designed by Schuenhoff et al. (2003) can purify and recycle 50% of the culture water. Deviller et al. (2004) added a seaweed pond in a recirculating water culture system for European sea bass (*Dicentrarchus labrax*) consisting of *Ulva lactuca*, *Enteromorpha*, and *Cladophora*. It can reduce N by 25% and P by 9% more than a common recirculating aquaculture system. A commercial integrated aquaculture system for sea bream, abalone, and macroalgae filter ponds has been operated in Israel (Neori et al. 2004).

10.2.3 Solar Recirculating Aquaculture Systems Based on Microalgae

The high photosynthetic efficiency of phytoplankton in the pond allows for efficient uptake of nutrients in the water. High-rate algal pond (HRAP) can also be used to treat wastewater discharged from RAS. Figure 10.5 shows an HRAP-based RAS for European perch (*Dicentrarchus labrax*) designed by Metaxa et al. (2004). Components 1–9 of this system constitute a complete RAS. Water disinfected by UV light (6) can partially flow into HRAP (10), and clean water purified by the phytoplankton in the pond is returned back to the RAS. Compared with the single RAS system, the addition of HARP results in significantly higher survival and growth rate of cultured fish, a 25% reduction in TN, and a 9% reduction in TP in the water (Deviller et al. 2004). HRAP is a specially designed water purification system (Racault and Boutin 2005), and HRAPs in good operation have a removal efficiency of up to 175 gBOD/(m^3·d), compared with 5–10 gBOD/(m^3·d) in common ponds.

Phytoplankton in HRAP absorbs dissolved nutrients discharged from the RAS. However, large amounts of phytoplankton produced by HARP must also be utilized, otherwise they will cause secondary pollution to the environment. The phytoplankton biomass can be harvested by flocculation and can also be utilized through the culture of filter-feeding fish and shellfish (Martins et al. 2010).

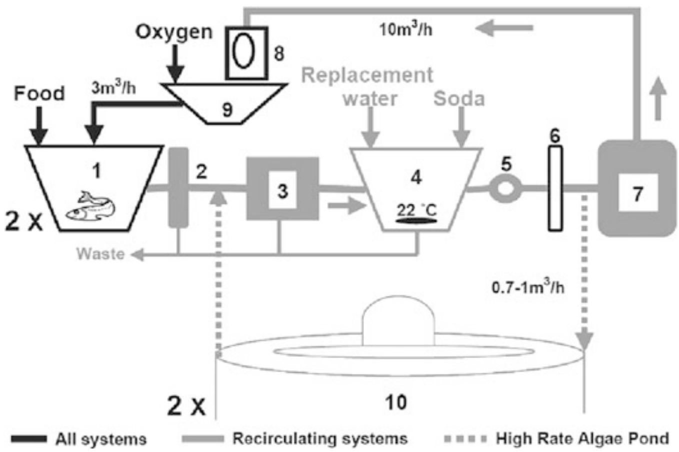


Fig. 10.5 Schematic diagram of high-rate algal pond (HRAP)-based RAS (from Metaxa et al. 2004). (1) Fish tank; (2) Particle trap; (3) Mechanical filter; (4) Pumping tank; (5) Pump; (6) UV lamp; (7) Biological filter; (8) Packed column; (9) Storage tank; (10) HRAP.

Other forms of microalgae-based recirculating aquaculture systems are possible depending on the type of animals cultured, water resources, quality requirements for discharge water, surrounding environment, market demand, etc. HRAP units can also be common aquaculture ponds.

10.3 Raceway Aquaculture Systems

Raceway aquaculture systems are the aquaculture systems that form high water flow in proportion to their volume in relatively shallow waters in order to sustain aquatic organisms. Raceway aquaculture systems include flow-through raceways, loop raceways, and in-pond raceways. Water flow in the systems can make fish metabolites diluted and dissolved oxygen replenished in time, thus achieving high productivity.

10.3.1 Conventional Raceway Aquaculture Systems

Flow-through raceways and loop raceways are conventional raceway aquaculture systems. Flow-through raceway aquaculture systems are found in mountainous or hilly areas with sufficient gradient, where creeks or springs flow by gravity through earthen ponds or concrete tanks connected in series. Compared with earthen systems, concrete raceways can increase production 25%–40% using the same quantity of water (Fornshell 2002). Because of the high altitude and proximity to the source of the stream, these aquaculture systems are often used to culture cold water fish and those with high water quality requirements such as trout and sturgeon.

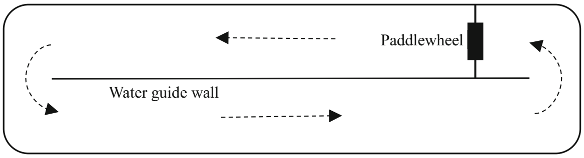


Fig. 10.6 Schematic diagram of loop raceway aquaculture system.

Compared with earthen ponds the productivity of flow-through raceways is much higher. In addition, flow-through raceways also offer a much greater ability to observe and monitor the growth and mortality of cultured fish. Its management such as size grading and harvesting are also easier. The greatest disadvantage of flow-through raceways is the constant discharge of wastes into the receiving river, which has drawn concern of the public and led to the enactment of strict environmental regulations in some countries.

Another type of conventional raceway aquaculture system is the loop raceway system (LRS), the basic structure of which is shown in Fig. 10.6. LRS is equipped with water pushing devices such as paddlewheel, which can drive the water flow in the loop raceway. The outdoor loop raceway aquaculture system is often used to culture phytoplanktons, such as *Spirulina*, *Chlorella pyrenoidosa*, and *Dunaliella salina*. These phytoplanktons can be made into health products, feed or biofuel, etc. (Pawar 2016). Loop raceway systems built indoors are commonly used to culture phytoplankton, fish, shrimp, etc. The water flow created in the raceway facilitates the growth of cultured organisms.

10.3.2 In-pond Raceway Aquaculture Systems

In-pond raceway system (IPRS), also known as in-pond recirculating aquaculture system, etc., is the combination of traditional raceway system and pond aquaculture system. IPRS was first developed by Auburn University in the early 1990s (Masser 2012) and then extended to China by the aquaculture experts from U.S. Soybean Export Council.

10.3.2.1 Structure and Principle of IPRS

The IPRS is a paradigm of partial intensification of traditional aquaculture system. A complex IPRS in a pond consists of a flow-through raceway area, a faces and residual collection area, a mollusk rearing area (in seawater), and an aquatic plant (seaweed) planting area (Fig. 10.7), thus achieving a step-by-step utilization of input feeds. More detailed structural design can be found in the literatures by Masser (2012), Yu and Wang (2016), and Wang et al. (2019a, b).

The fish rearing area consists of airlift pumps or paddle wheels and a number of fish rearing raceways. Airlift pumps or paddle wheels can effectively add oxygen into the water in addition to creating a directional water flow in the raceways. The velocity of flow in the raceway can be controlled by the power of the pumps or paddle wheels. Auburn University experts recommend that the flow velocity in the

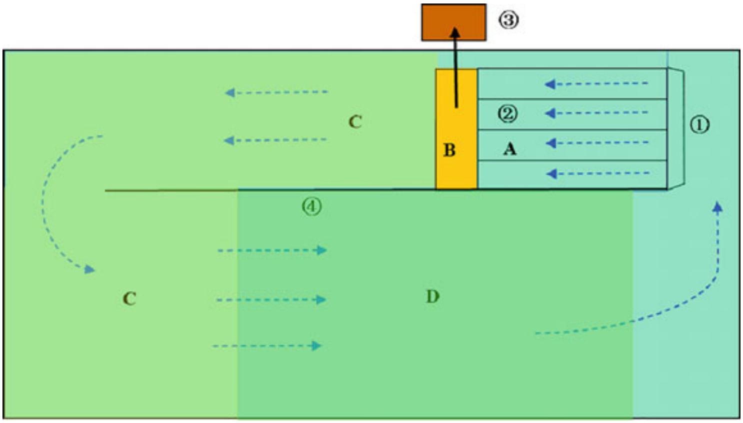


Fig. 10.7 Schematic diagram of In-pond raceway system in seawater. (1) Air lift pumps, (2) Fish rearing raceway, (3) Settling chamber for faces and residue, (4) Water guide wall; (**a**) Fish rearing area, (**b**) Faces and residue collecting area, (**c**) Mollusk rearing areas, (**d**) Aquatic plant or seaweed planting area.

raceway should generally be controlled at about 0.06–0.09 m/s, but the specific flow rate needs to be determined based on the cultured species, fish size, stocking density, feed types, etc.

The feed residue and feces collecting area consists of a collection area and a solids-settling chamber. The larger-sized feed residue and feces in the raceway will be settled in the collection area. A short wall at the end of this area can form an eddy or relatively static flow area, which will accelerate the sedimentation of feed residue and feces. The sedimentation rate of them can also be controlled by the velocity of flow generated by the pumps or paddle wheels. The feed residue and feces are then transferred by a suction device to the settling chamber, and treated there. Due to the artificial treatment of large particles of residual feed and feces produced by cultured fish, the carrying capacity of IPRS has been enhanced significantly compared with that of traditional polyculture ponds.

The function of the mollusk rearing area is the utilization of fine-grained organic matter. The water flowing from the residual feed and feces collection area also contains living planktons, fine particles of residual feed and feces, and dissolved substances. The filter-feeding mollusk in the raft or bottom-sowing area can use the fine-grained organic matter and convert these 'wastes' into aquatic food products. The mollusk rearing area can also be bottom-sowing with deposit-feeding animals, such as sea cucumber *Apostichopus japonicus* in seawater ponds of northern China.

The function of the aquatic plant or seaweed planting area is to absorb and utilize the inorganic nutrient dissolved in the water. The water flowing from the mollusk rearing area still has a large amount of dissolved inorganic nutrients that mollusk cannot utilize. Aquatic plants such as macrophyte (macroalgae) in this area absorb these inorganic nutrients and convert them into aquatic food products.

Table 10.3 Comparison of IPRS with cage, pond, flow-through raceway, and RAS (from Masser 2012)

Systems	IPRS	Cage	Pond	Flow-through raceway	RAS
Stocking density	1	–	–	=	–
Food conversion ratio	1	–	–	=	=
Production/area	1	–	–	=	–
Overwintering	1	=	+	+	+
Labor	1	–	–	=	–
Economic efficiency	1	–	–	+	–
Water quality	1	–	–	+	+
Solid waste removal	1	–	–	–	+

Note: + be superior to, = similar to, - inferior to

The zoned culture of mollusk and macrophytes (macroalgae) is helpful for management. Of course, they may be co-cultured in the same area in practice. Filter-feeding mollusk can also be replaced by filter-feeding fish. The co-cultured filter-feeding fish can be distributed in the remaining areas of the pond except for the fish rearing raceway and the residual feed and feces collection area.

Compared with a fish pond aquaculture system, an IPRS in good operation has the following advantages:(1) Easy to manage. Since farmed fish (except filter-feeding fish in free range) are cultured in the raceway and mollusk and aquatic plants are also stocked in different areas of the pond, it is easier to implement harvesting and intelligent management. (2) High feed utilization rate. Since fed fish are cultured in the raceway and can be fed centrally, it is easier to observe the feeding activity of the fish and achieve appropriate feeding satiation. Especially, when floating feed is given, it can keep the feed trapped within the raceway, resulting in reducing feed loss. (3) Higher fish yield. Since IPR is environmentally superior in terms of solid waste removal including residual feed and faces, the carrying capacity and fish yield of the system are higher. (4) More energy saving. Since the aeration is only supplied in the flow-through raceway, power expenditure is reduced. (5) Less waste discharge, even zero discharge. Since the residual feed and faces collection area, mollusk culture area, and macrophyte (macroalgae) planting area can collect, absorb, and utilize the large particles of residual feed and faces, fine particles of organic matter, and dissolved inorganic nutrient, it is easier to meet the requirements of effluent discharge standards. If the proportions between each functional area are designed and set properly, IPRS can also realize zero discharge of organic matters. (6) More feasible to multi-species and multi-specification culture practice according to market demand. Since each raceway unit can operate independently, it is possible to realize multi-species and multi-specification culture in separate units to meet the market demand for continuous and characteristic products (Masser 2012). In addition, a certain water flow in the raceway will have a favorable impact on the quality of cultured fish as well (Liu et al. 2019).

IPRS has some significant advantages over net cage, conventional raceway, and recirculating aquaculture systems (Table 10.3), and is one of the best-extended aquaculture systems among land-based intensive aquaculture systems.

10.3.2.2 Carrying Capacity of IPRS

As a conservative design benchmark, a culture raceway (5 m^3 × 22 m^3 × 1.5 m^3) in temperate regions requires 6666 m^2 (=10 acres) of pond water with an average depth of 1.5–2.0 m, according to the recommendations of Auburn University experts. In tropical areas, the ratio of raceway to pond water can be considered appropriately increased.

The base carrying capacity of IPRS can be estimated by the productivity of the whole pond culture system. It is generally believed that the fish productivity of conventional ponds ranges from 0.5 to 0.6 kg/m^3, from which the productivity of the entire pond can be calculated. With the data on the productivity of the whole pond, the fish loading of the raceway area can be obtained by dividing it by the raceway volume, and the stocking number and biomass of fish fingerlings can also be estimated accordingly.

Considering the role of removing feces and residual feed in the collection area and the purification capacity of the pond to the excreted wastes derived from farmed fish, the experts from Auburn University suggest that the fish productivity in a pond installed IPRS can reach 1–1.5 kg/m^3. Therefore, the fish productivity of a pond installed IPRS with an average water depth of 1.7–2.0 m can reach 20,000–25,000 kg/(hm^2·yr).

The carrying capacity of IPRS is related to many factors, such as the volume of pond, culture species, feed quality, aeration efficiency of the air lift pumps or paddle wheels, and the purification capacity of the mollusk rearing area and macrophyte planting area. Therefore, the carrying capacity of an IPRS should be analyzed on a problem-specific basis and there is no uniform parameter.

The ratio of raceway volume to whole pond volume is a key parameter for IPRS design. According to the estimation of Yang and Guan (2019), the volume ratio of raceway with 100 kg/m^3 fish and whole pond could be 1.03%–1.55% and 1.18%–1.77%, respectively, when the collection efficiency of residual feed and faces is 30 and 60%.

The aeration and water flow generated by air lift pumps or paddle wheels make partial intensification of pond farming possible, but a suitable density of cultured fish is still very important. For example, the optimal stocking density of GIFT tilapia (*Oreochromis niloticus*) in IPRS is 90 ind./m^3 (Wang et al. 2019a, b). Obviously, low stocking density is not conducive to realizing the production potential of IPRS, while over-stocking will influence the physiological status of cultured fish (Wang et al. 2019a, b) and the community structure of fish intestinal microbiota (Li et al. 2020).

The carrying capacity of IPRS needs further study if the effluent is considered to meet the requirements of discharge standards or achieve zero discharge of waste.

10.3.2.3 Ecological and Economic Benefits of IPRS

According to trial data of Auburn University, the yield of spotted catfish using freshwater IPRS installed in a pond (Fig. 10.8, left) is significantly higher than that of net cages and ponds, while the costs are significantly lower than that of net cage and pond culture, in a total culture water area of 0.4 hm^2 (Table 10.4). The N and P utilization efficiency of spotted catfish for input feeds in IPRS are 34.0% and 34.1%, respectively (Brown et al. 2012). Therefore, IPRS is more economically and ecologically efficient than ponds and net cages for spotted catfish farming.

A comparative study was conducted on an IPRS (Fig. 10.8, right) set up in a seawater pond (4 hm^2 in area) and a conventional polyculture pond (4 hm^2 in area, 1.8–2.0 m in depth) for puffer fish (Li 2020). The structure of the IPRS is similar to Fig. 10.7, and the cultured species include puffer fish (*Takifugu rubripes* and *T. flavidus*), sea bass (*Lateolabrax maculatus*), filter-feeding clam (*Mercenaria mercenaria*), and aquatic plant (*Sesuvium portulacastrum*). Among them, puffer fish and sea bass are stocked in raceway, clams are bottom sowing in the pond, and aquatic plant grows in floating rafts. The culture species of polyculture pond are puffer fish, swimming crab (*Portunnus trituberculatus*), and Chinese shrimp (*Fenneropenaeus chinensis*). For IPRS, the survival rates of *T. rubripes*, *T. flavidus*, sea bass, clams, and aquatic plant in the IPRS are 78.8%, 95.4%, 72.2%, 45.2%, and 98.8%, respectively, while those of *T. rubripes*, swimming crab, and Chinese shrimp in the polyculture pond are 76.4%, 5.66%, and 2.23%, respectively. The total production of the IPRS is significantly higher than that of the polyculture pond.

Fig. 10.8 In-pond raceway systems. Left photo, IPRS for freshwater channel catfish in Alabama, USA; Right photo, IPRS for seawater puffer fish in Hebei, China

Table 10.4 Economic comparisons between IPRS, cages, and pond catfish culture (0.4 hm^2 pond; from Masser 2012)

Systems	IPRS	Cage	Pond
Yield (kg)	2433	1286	1730
Death loss (%)	10	10	6
Feed conversion efficiency	1.45	1.6	1.8
Protein content of feed (%)	36	36	32
Total costs ($)	5272	3241	3923
Breakeven price ($/kg)	2.17	2.52	2.27

Table 10.5 Energy conversion coefficients in in-pond raceway systems and earthen seawater pond systems (from Li 2020)

Parameters	IPRS	Pond
Total yield (MJ)	201843.20 ± 1274.23[a]	39515.25 ± 534.27[b]
Photosynthetic conversion efficiency (%)	0.11 ± 0.03[a]	0.04 ± 0.01[b]
Feeding energy conversion efficiency (%)	57.48 ± 6.29[a]	14.05 ± 1.53[b]
Total energy conversion efficiency (%)	40.37 ± 1.52[a]	16.43 ± 0.93[b]
Feeding energy consumption per unit of net yield (MJ/Kg)	10.14 ± 2.08[a]	54.85 ± 6.05[b]
Total energy consumption per unit of net yield (MJ/Kg)	10.63 ± 2.19[a]	55.01 ± 7.67[b]

Note: Photosynthetic conversion efficiency = Total yield (MJ)/Solar energy (MJ) × 100%, Feeding energy conversion efficiency = Total yield (MJ)/Feeding energy (MJ), Total energy conversion efficiency = Total yield (MJ)/Total input energy (MJ), Feeding energy consumption per unit of net yield = Feeding energy (MJ)/Total yield (Kg), Total energy consumption per unit of net yield = Total input energy (MJ)/Total yield (Kg)

N and P from residual feed and faces account for 10.6 and 16.1% of total N and P expenditures, respectively, in IPRS, while the corresponding values were 31.7% and 21.1%, respectively, in the polyculture system. The utilization efficiencies of N and P in IPRS are 29.2% and 15.3%, respectively, while those in polyculture system are 4.91% and 3.17%, respectively. Therefore, IPRS can not only improve the utilization efficiency of N and P compared with the polyculture system, but also can use the water resources more effectively and reduce the pollution to the receiving waters.

IPRS is significantly higher than the polyculture system in terms of net biological yield energy, photosynthetic conversion efficiency, feeding energy conversion efficiency, and total energy conversion efficiency. However, its feeding energy consumption per unit of net yield and total energy consumption per unit of net yield are significantly lower than the polyculture system (Table 10.5).

IPRS is being extended very fast, especially in China. According to incomplete statistics, there are now more than 6000 aquaculture raceways in China, and more than 20 species have been cultured. However, IPRS in China is mainly applied in freshwater aquaculture, and IPRS in mariculture is still less reported.

The average water consumption of grass carp in IPRS is 460 m^3/t, which is 78.5% less than that of common pond culture; IPRS discharges 57% less waste (Wei et al. 2018). According to data from four IPRSs in Hangzhou, Zhejiang province, water quality in IPRS is significantly improved, with an average decrease of 41.5% in total nitrogen, 23.65% in total phosphorus, and no water exchange during the culture duration (Ma et al. 2019).

IPRS is a model for the implementation of partial intensification of aquaculture ponds, and has some significant advantages over other land-based intensive aquaculture systems. Generally, the IPRS simplifies feeding, grading, harvest, and disease treatments, which reduces labor requirements compared with other systems. IPRS appears to be more environmentally sustainable than cages, raceways, and intensive open-pond production. However, according to current practices in China, the economic benefits of IPRS for different regions still vary greatly. For example, in Anhui Province, the yield of IPRS in good operation can be 50–150 kg/m^3, the average yield is 35–75 kg/m^3, and the lower one is 15–50 kg/m^3. As for culture benefits, the profitable, loss-generating, and break-even IPRSs are one-third of each among those in operation. Therefore, there are still many problems for IPRS needed to be resolved and many technologies need to be improved. Particularly, cost-effective solid and liquid waste reduction methods need to be evaluated and further developed. Moreover, more attention is generally paid to the construction of flow-through raceways rather than water purification function in IPRS, which needs more technological innovation and proper guidance for this aquaculture system.

10.3.3 Local Intensification of Aquaculture Ponds

The essence of IPRS is the local intensification of an aquaculture pond, i.e., intensive modification of the fish rearing area in a pond (Fig. 10.7). Because the runways use whole water of the pond, coupled with the aeration effect of air lift pumps, the output of the runways is not lower than that of an ordinary pond with the same area. There are other forms of local intensification of aquaculture ponds, such as local aeration and feeding of pond and split-pond system.

10.3.3.1 Local Aeration and Feeding of Pond

Fig. 10.9 is an aquaculture system of local aeration and feeding of pond for co-culture of grass carp and crucian carp in Panyu, Guangdong Province in China. The pond is divided into three areas, namely pond area (A), aeration and feeding area (B), and collection area of particle waste (C). The aeration and feeding area is provided with a feed jet nozzle (1) and aeration plates (2). The bottom of the collection area of particle waste is a hardened funnel, and a waste collecting hole (5) is arranged in the center. The pelleted feeds are sprayed into the air through feeding pipe (4) and nozzle, and then fall into the aeration and feeding area. When the farmed fish swim to this area for feeding, the aeration begins to work. At a period of time before and after fish feeding paddle wheels (3) operate to drive feed residue

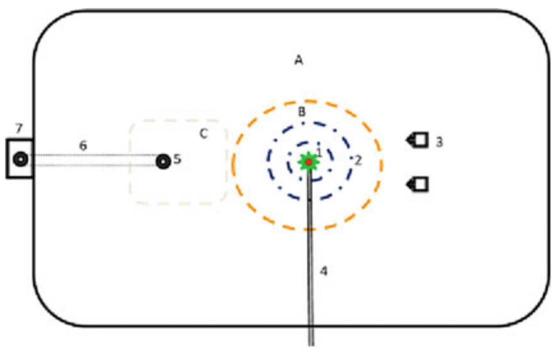


Fig. 10.9 Top view of local aeration and feeding pond. (**a**) pond area, (**b**) aeration and feeding area, (**c**) collection area of particle waste; (1) feed jet nozzle, (2) aeration plates, (3) paddle wheels, (4) pipes of feeding and aeration, (5) waste collecting hole, (6) waste collection channel, (7) waste collection well.

and feces to the collection area of particle waste. The particle waste is pumped out regularly from waste collection well (7) through waste collection channel (6).

Like IPRS, the aquaculture systems of local aeration and feeding of pond also function as centralized feeding, residual feed, and feces collection. The oxygen consumption intensity of fish during feeding is high and all of them are concentrated in the aeration and feeding area. Aeration in this area can meet the demand of fish respiration, and can save energy. In addition, at night, when phytoplankton photosynthesis stops and the pond is hypoxic, aeration is needed only in the aeration and feeding area. Therefore, the aquaculture systems of local aeration and feeding of pond have the advantages of energy saving and high yield compared with common aeration ponds.

10.3.3.2 Split-pond System

Split-pond system is another example of local intensification of aquaculture ponds, and was developed in the 1990s to exploit existing catfish ponds for building zero-discharge of aquaculture systems (Boyd et al. 2020). Split-ponds are built by constructing an earthen levee and dividing the pond into two sections (Fig. 10.10), in which water is circulated between the two sections with pumps, but only fish-holding basin is aerated or intensified. Split-ponds have a relatively larger algal basin or water treatment section (about 80%–85% of the total area) and a smaller fish basin. Compared with IPRS, the fish basin stocks fish at much lower densities in order to afford a safety margin against unexpected accidents such as loss of electrical power. Catfish production in commercial-scale split-ponds in the southeastern United States is 14–18 t/ha.

10.3.3.3 Net Cages in a Pond

Another example of local intensification of an aquaculture pond is a fish cage in a pond (Fig. 10.11 left). The cage in the pond has functions similar to the system of local feeding and aeration. In the pond of waterlogged salt-alkali land, which lacks freshwater resources normally, it is convenient to catch common carp in the cages

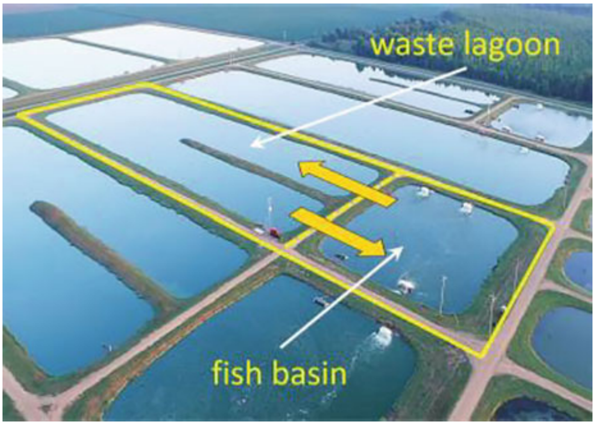


Fig. 10.10 Split-ponds for ictalurid catfish in Mississippi, USA (Boyd et al. 2020). The middle pond is highlighted to show partitioning of the original 3.2-ha pond into a 0.6-ha fish-holding basin and a 2.6-ha algal waste-treatment lagoon. Arrows show direction of daytime pumped-water circulation through culverts.

Fig. 10.11 Fish cages in a pond (left) and fish farming with containers (right)

and can save water. Since common carp are a benthic fish, thorough harvesting of the carp outside the cages usually requires draining the pond. In addition, tilapia kept in the cages can still regulate water quality but do not compete pelleted feed with the shrimp outside the cages (Sun and Dong 2010; see Sect. 11.5.3 for detail). Furthermore, the use of pond cages for tilapia farming in the pond can prevent tilapia from spawning.

Fish farming with containers (Fig. 10.11 right) is also a land-based intensive aquaculture system in China. It is easy to disassemble and assemble, and not strict to the operation site requirements. It is suitable for fish farming at the corner and spare land, such as using the cooling water of a power plant to culture tilapia, and also suitable for implementing aquaculture on sandy land. To supply water to the containers, it needs to lift several meters of water head compared to other local intensification systems, and requires additional energy consumption. Therefore, it is not recommended to carry out container farming activities except for special needs.

10.4 Biofloc-based Aquaculture Systems

Feeding strategies in pond culture are divided into two categories: those that feed high-protein feeds whose nutrients largely meet the needs of cultured animals, and those that feed low-protein feeds based on crop products and rely on natural foods to supplement the nutrient-deficient portion of the feed. The natural foods utilized by cultured animals are usually photosynthesis-based primary and secondary producers in aquaculture systems. This section focuses on natural foods based on heterotrophic bioflocs. Biofloc-based aquaculture systems emerged in the 1990s, and widely farmed species now are tilapia and shrimp, which can directly utilize natural productivity (Browdy et al. 2012).

10.4.1 Introduction to Biofloc-based Aquaculture Systems

With increasingly stringent restrictions on the waste discharge of aquaculture systems, coupled with the worldwide spread of epidemic viral diseases in shrimp, attention has been focused on the development of closed, non-feeding aquaculture systems based on microbial communities. The concept of establishing heterotrophic food web-based aquaculture systems was proposed by Israeli scientists in the 1970s and 1980s, and later developed with the support of Solar Aquafarms in Israel, a biofloc culture system that is commercially operated today (Browdy et al. 2012). In the early 1990s, two groups at the Technion University of Israel and at the Waddell Mariculture Center of the United States systematically studied biofloc-based culture technologies for tilapia and shrimp with reduced and then zero exchange, respectively (Avnimelech 1993; Hopkins et al. 1994).

In terms of culture types, biofloc-based culture is available in outdoor earthen, lined and raceway ponds, indoor ordinary concrete ponds, and recirculating aquaculture systems. The single-crop yield of this system for farmed shrimp is 1–2 kg/m^2, with a high of 10 kg/m^2; the biomass of farmed tilapia can reach 10–30 kg/m^2 (Browdy et al. 2012).

The average utilization of organic carbon, nitrogen, and phosphorus in feeds by typical aquaculture animals is 13%, 29%, and 16% respectively, and unused nutrients also need to be mechanically filtered out, sedimented, microbially transformed, or drained directly from the culture system. In contrast, for a biofloc-based aquaculture system, feeding is not necessary in low-density culture system, and farmed fish and shrimp can utilize the biofloc formed by the microbial community. In higher-density culture system, supplemental low-quality feed is required; however, residual feed and faces can be decomposed and utilized by microorganisms, then formed into biofloc (nutrients) that can be utilized by farmed animals. In RAS, the surface of the biofilter also hosts or cultivates a large number of microorganisms, whose function is mainly to decompose the metabolites of the farm animals, while the microorganisms in the biofloc-based aquaculture system are both waste decomposers, transformers, and food for farmed animals.

Bioflocs are widely found in aquatic ecosystems and contain mainly inanimate humid acids, proteins, fats, polysaccharide compounds, etc., but also animate bacteria, fungi, viruses, various phytoplankton, protozoa, ciliates, nematodes, etc. The general biofloc dry matter contains 25%–50% crude protein and 0.5%–15% crude fat.

Biofloc particles in biofloc-based aquaculture systems can be as large as a few millimeters and can be directly ingested by farmed fish and shrimp. Generally, the presence of floc particles larger than 5 μm can contribute to increased shrimp production (Moss and Pruder 1995). The size of floc particles in biofloc-based aquaculture systems is related to the aeration method and intensity, etc. The sizes of biofloc particles vary among culture systems. The systems with more water pumping activity tend to have smaller particles, while the systems with airlift mechanisms tend to have larger particles.

A biofloc is a micro-ecosystem in itself, with multiple ecological functions. Addition of carbon or/and carbohydrates is required for the cultivation of the floc microbial community, and aeration and pH adjustment are required for the maintenance of good water quality for the cultured animals and microorganisms.

Biofloc-based aquaculture technology provides disease prevention for shrimp in three ways: Firstly, the closed system and less water exchange rate reduce the possibility of harmful exogenous pathogens invading the culture system and enhance the biosecurity of the culture system. Secondly, microorganisms in bioflocs compete with pathogenic bacteria for living space and nutrients, disrupting the quorum-sensing system of pathogenic bacteria and thus inhibiting the growth and reproduction of pathogenic bacteria in the water. Thirdly, bioflocs contain a variety of bacteria and their secretion products, such as poly-β-hydroxybutyric acid, polysaccharides, and other active substances, which are likely to have growth-promoting and immune-enhancing effects on farmed animals.

The main advantages of a well-run biofloc-based aquaculture system include: (1) Less energy consumption. Since the cost of aeration is usually lower than the cost of water exchange, the energy costs of a biofloc-based aquaculture system will be lower than that of a culture system that requires flow-through water or large water exchange. (2) Less or no high-protein feed required. Tilapia and shrimp cultured in biofloc systems can feed on the natural food incubated in the system and do not require high-protein feeds, only carbon or/and carbohydrates for cultivating microbial communities are added to the system. (3) Water saving. The system requires essentially no water exchanges and usually only the water lost to evaporation needs to be supplemented. (4) Good prevention of shrimp epidemics. First of all, the system is a closed system, less susceptible to foreign pathogens; secondly, the microbial community in the system can effectively inhibit pathogenic microorganisms of farmed shrimp. (5) Possible zero discharge. The system does not need water exchange. (6) Land saving. Compared with some open ponds, the system occupies less land and has lower costs of leased land.

10.4.2 Water Quality in Biofloc-based Aquaculture Systems

Like other aquaculture systems, biofloc systems undergo a process of community succession or maturation, from the receiving impoundment to the formation of a stable biological community in the system, with corresponding changes in water quality. The main ecological processes affecting water quality in the systems include photosynthesis, heterotrophic assimilation, nitrification, and denitrification.

10.4.2.1 Photosynthesis of Phytoplankton

When the outdoor culture system is activated under adequate light, the first thing that is seen is that the water color gradually turns to green. Then, the phytoplankton community grows in an exponential phase, and finally self-shading occurs due to high density. After that, the system starts to change from a type dominated by phytoplankton autotrophy to the one dominated by microbial heterotrophy. This transition is accelerated by insufficient light and high feeding rates. During this period, the dissolved oxygen, CO_2, pH, etc., in the water also change regularly with the relative changes in the intensity of photosynthesis and microbial ‘water respiration’.

The accumulation of bioflocs also reduces the light intensity in the water, which affects the uptake of ammonia nitrogen by phytoplankton. In addition, even under strongly aerated conditions, dissolved oxygen contents show regular diurnal fluctuations. Generally, when the daily feeding rate is below 30 g/m^2, phytoplankton photosynthesis will be the main factor controlling water quality. As the feeding rate increases, the biological community in the system will change from phytoplankton dominated to bacterial community dominated (Xu 2014).

10.4.2.2 Assimilation of Bacteria

Early biofloc microbial communities are predominantly heterotrophic, with heterotrophic bacteria using residual feed and feces as a carbon and energy source. Heterotrophic bacteria and other microorganisms use carbohydrates (sugars, starch, and cellulose) as a food to generate energy and to grow (Browdy et al. 2012):

$$\text{Organic C} \rightarrow CO_2 + \text{Energy} + \text{C assimilated in microbial cells.}$$

The percentage of the assimilated carbon with respect to the metabolized feed carbon is defined as the microbial conversion efficiency (E) and is in the range of 40–60%. Of course, the microbial cells assimilate organic C from feeds and also assimilate organic N from residual feeds and faces at the same time.

Due to the continuous input of protein-containing feeds, the content of soluble nitrogen (including inorganic and organic nitrogen) in the water of culture systems will continue to increase, and the deficiency of soluble organic carbon becomes a limiting factor for the growth and reproduction of heterotrophic bacteria. In aquaculture practice, the *C*/*N* of the water environment is often increased by adding organic carbon sources (sugars, starch, and cellulose) or by reducing the protein content of the feed to maintain a healthy microbial community. The amount of carbon assimilated by microorganisms (ΔC_{mic}) and the amount of carbohydrate supplement (ΔCH) required to reduce the ammonium can be calculated as follows (Avnimelech 1999):

$$\Delta C_{\text{mic}} = \Delta \text{CH} \times \%C \times E$$

where $\%C$ is the carbon contents of added carbohydrate (roughly 50% for most substrates).

The amount of nitrogen needed for the production of new cell material (ΔN) depends on the *C*/*N* ratio in the microbial biomass, which is about 4.

$$\Delta N = \Delta C_{\text{mic}} / (C/N)_{\text{mic}} = \Delta \text{CH} \times \%C \times E / (C/N)_{\text{mic}}$$

And using approximate values of $\%C$, E, and $(C/N)_{\text{mic}}$ as 0.5, 0.4, and 4, respectively:

$$\Delta \text{CH} = \Delta N / (0.5 \times 0.4/4) = \Delta N / 0.05$$

Thus, the CH addition needed to reduce total ammonia nitrogen (TAN) 1 mgN/L (i.e., 1 gN/m^3) is 20 mg (20 g/m^3). This relationship enables a manager of culture ponds to calculate how much carbohydrate substrate must be added to reduce ammonia nitrogen in an emergency (Browdy et al. 2012).

With the excretion of cultured animals and decomposition of residual feed and faces, inorganic nitrogen in the water begins to accumulate gradually. At a certain pH, temperature, and salinity, a corresponding balance between NH_3 and NH_4^+ is also established. NH_3 in the system can be utilized or transformed by phototrophic autotrophic bacteria (cyanobacteria) and autotrophic nitrifying bacteria.

10.4.2.3 Nitrification of Bacteria

As the concentration of ammonia and nitrogen in the water environment gradually increases, under aerobic conditions, nitrifying autotrophic bacteria begin to convert NH_3, which is toxic to farm animals, into NO_2^- and NO_3^- in steps through nitrification. If the feeding rate is too high at the early stage of system establishment, the peak concentration of NH_3 and NO_2^- will appear rapidly in the system (Fig. 10.9), and the high concentration will also affect the growth of cultured animals and even cause fatal injury to them.

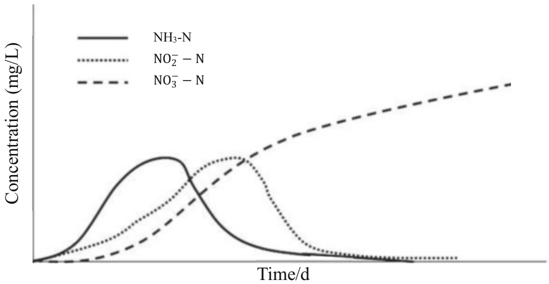
Nitrification is a slow, long-term process, but eventually 25%–50% of input feed nitrogen will be converted to nitrate nitrogen in the process. This mechanism is particularly important in farming systems with a high degree of intensification, i.e., a high feeding rate.

The addition of organic carbon sources can be stopped after the nitrifying bacteria has developed and reached stability in the biofloc aquaculture system. The gradual accumulation of nitrate nitrogen is a characteristic of strong nitrification over heterotrophic assimilation and denitrification (Fig. 10.12).

10.4.2.4 Denitrification of Bacteria

Nitrate (NO_3^-) can be reduced to nitrogen gas (N_2) through denitrification under anaerobic conditions, resulting in the removal of N_2 from the aquaculture system. Due to high aeration intensity, the biofloc aquaculture system as a whole is in an aerobic state; however, local anoxia can occur inside the biofloc particles, and denitrification also occurs in the system. Therefore, the nitrogen balance in the biofloc aquaculture system is more complex. Denitrification is conducted by

Fig. 10.12 Typical nitrification startup curves (from Browdy et al. 2012)



heterotrophic bacteria capable of utilizing NO_3^- in the absence of O_2 to produce nitrite (NO_2^-) and then N_2 as a product.

10.4.3 Regulation of Water Quality in Biofloc-based Aquaculture System

During the development, maturation, and stabilization of biofloc aquaculture system, in order to maintain good water quality, the manager needs to adjust C/N and pH of the water, supply oxygen to the system, control the density of biofloc, etc.

10.4.3.1 C/N Regulation

The stoichiometric balance of ammonia nitrogen nitrification and heterotrophic assimilation occurring in biofloc aquaculture system is shown in Table 10.6. Heterotrophic assimilation requires applying about 15.17 g of carbohydrate for removing 1 g of ammonia-nitrogen. Therefore, carbohydrates should be added to the system during the active phase of heterotrophic assimilation.

Feeds for aquatic animals usually contain high crude protein with a C/N ratio of 6–10, while the C/N suitable for heterotrophic bacteria to assimilate ammonia nitrogen is about 12–15. The C/N of the aquatic environment can be improved by adding organic carbon sources to the water or using low protein content compound feeds during the culture process. Organic carbon sources commonly used in aquaculture practice are simple carbohydrates, such as glucose, sucrose, etc., and complex carbohydrates, such as starch, tapioca, cereal flours, etc. The former has the advantage of being fast-acting and the disadvantage of requiring continuous application. The latter is characterized by the opposite of the former. Simple carbohydrates can be applied at the beginning of a biofloc aquaculture system operation or for emergency C/N regulation. Complex carbohydrates should also be applied initially for the purpose of continuous and stable C/N regulation thereafter.

When using feeds containing 30%–38% crude protein, theoretically 0.5 or 1.0 kg of carbohydrates is required for every 1 kg of feed delivered. The amount of carbohydrates applied can be reduced if there is photosynthesis in the water that can absorb ammonia nitrogen. Obviously, applying such a great amount of

Table 10.6 Comparison of stoichiometric balances for removing 1 g of ammonia-nitrogen by nitrification and heterotrophic assimilation (from Ebeling et al. 2006)

	Nitrification (g)	Heterotrophic assimilation (g)
Carbohydrate consumed	0	15.17
Alkalinity consumed	7.05	3.57
Oxygen consumed	4.18	4.71
Bacterial biomass produced	0.20	8.07
CO_2 produced	5.85	9.65
$NO_3^- - N$ produced	0.976	0

carbohydrates is a significant cost, so the search for cheaper complex carbohydrates to replace simple carbohydrates is a hot issue of concern.

10.4.3.2 pH Regulation

Nitrification consumes great amounts of alkalinity (bicarbonate) and produces CO_2, which lowers the pH of the aquatic environment (Ebeling and Timmons 2007):

$$NH_4^+ + 1.83O_2 + 1.97HCO_3^- \rightarrow 0.0244C_5H_7O_2N + 0.976NO_3^- + 2.90H_2O + 1.86CO_2$$

Therefore, failure to observe and adjust pH in a timely manner can affect the growth of cultured animals and shrimp molting. Both alkalinity and oxygen are consumed by nitrification or heterotrophic assimilation of ammonia in biofloc aquaculture systems, and nitrification in particular consumes more alkalinity. About 7.05 g of HCO_3^- is required for removing 1 g N to maintain alkalinity. Therefore, lime or sodium bicarbonate should be applied into the system routinely to replenish the depleted alkalinity and prevent a significant drop in pH to ensure good growth of nitrifying bacteria and farm animals. In an intensive autotrophic bacteria-dominated biofloc aquaculture system, about 0.25 kg of sodium bicarbonate is applied for every 1 kg of feed delivered. Of course, during actual farming operations, alkalinity is monitored regularly at least weekly and the amount of sodium bicarbonate applied is determined as needed.

10.4.3.3 Concentration Regulation of Biofloc Particles

The concentration or total suspended solids (TSS) of biofloc particles in biofloc-based aquaculture system is usually very high. High concentration of biofloc particles means more food for fish and shrimp, but at the same time the oxygen requirements of the water will be high as well, and the costs of aeration will be correspondingly high. High concentration of biofloc particles may result in gill clogging and hindering gas and ion exchange of the gill. Therefore, the concentration regulation of biofloc particle is an important task in the management of biofloc aquaculture systems. When suspended particle concentration is in the range of 100–300 mgTSS/L in a biofloc aquaculture system of raceway, it is advantageous for the feeding of shrimp. When the particles are in the range of 200–500 mgTSS/L the system operates well with moderate microbial oxygen consumption (Ray et al. 2010). Higher concentration of biofloc particles may increase aeration costs and stress on the culture animals.

For the biofloc aquaculture system of lined pond where the stocking density of shrimp and aeration intensity are not very high, concentration of biofloc particles should be lower. Biofloc concentrations are more beneficial for shrimp culture in a pond when the settling volume is 10–15 mL/L (Xu 2014). Phytoplankton in outdoor biofloc aquaculture systems are important participants in regulating water quality, and low concentration of biofloc particles can provide better light conditions for phytoplankton and facilitate photosynthesis.

The bottom of the aquaculture system can be regularly dredged with central sewers and settling ponds, or bioflocs can be regularly removed with foam fractionators, etc. Since heterotrophic assimilation requires a great input of carbohydrates and produces about 40 times more solid waste than nitrification, it is even more important to remove sludge from the system in a routine manner.

Biofloc technology has shown great promise for shrimp aquaculture. However, bioflocs themselves are still full of unknowns. The structure and function of bioflocs, their regulation, nutritional value, and growth-promoting factors still need to be studied in depth. Biofloc aquaculture systems require great amounts of electrical energy inputs, which not only results in a high carbon footprint of the aquatic products, but also limits the application of this aquaculture model in the areas with intense electricity supply and expensive electricity.

10.5 Development of Land-based Intensive Aquaculture Systems

Aquaculture originated from pond farming of freshwater fish. In the 1950s and 1960s, the extensive use of pelleted feeds and aerators promoted pond production significantly. Flow-through earthen ponds or concrete tanks in mountainous or hilly areas promoted the production of cold-water fish and those with high water quality requirements. With the rapid expansion of intensive pond farming, arable land use, freshwater consumption, and pollutant discharge have aroused people’s concern. Therefore, in order to alleviate the conflict with the agriculture in land and freshwater uses and to reduce the pollutant discharge, some land-based intensive aquaculture systems have been innovated along three technical routes, i.e., RAS, raceway, and bioflocs (Fig. 10.13).

The key of RAS is the treatment and recycling of aquaculture water, depending mainly physical dilution, microbial conversion of compounds as well as removal of particle wastes (Fig. 10.1). However, the aerobic environment of conventional RAS makes the denitrification in the system negligible, and the aerobic biofilter only changes NH_4^+ into NO_3^-, and the total dissolved inorganic nitrogen will accumulate in the system.

In order to deal with the problem of inorganic nitrogen accumulation, denitrification units or large aquatic plants or water treatment ponds are integrated into conventional RASs, forming modern RAS with denitrification function (Fig. 10.2), aquaponics (Fig. 10.3), solar SRASs (Fig. 10.4), high-rate algal pond-based RAS (Fig. 10.5), etc. Another technical route is to build land-based raceway aquaculture systems (Fig. 10.6), which can form circulating water flow in the aquaculture waters to dilute wastes and meet the requirements of farmed organisms. The third technical route is the biofloc aquaculture systems based on heterotrophic food web for culturing tilapia and shrimp, which have the functions of saving high protein feed and disease prevention.

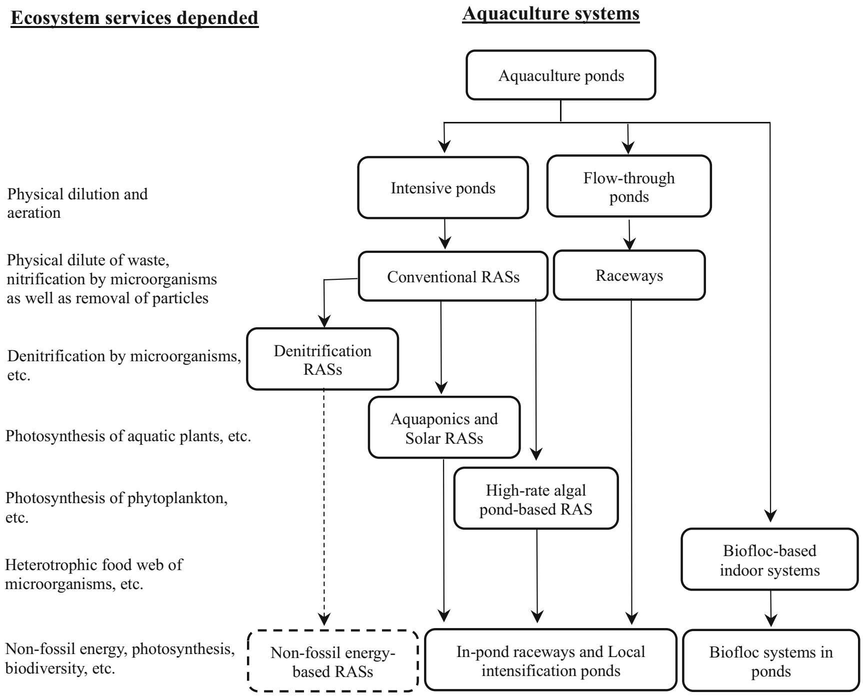


Fig. 10.13 Development of land-based intensive aquaculture systems and ecosystem services depended.

RASs, raceway systems, and biofloc systems are all energy-consuming aquaculture systems with high production cost. In order to make use of the natural purification capacity of outdoor pond, outdoor biofloc systems and local intensification of pond systems are developed, such as in-pond raceways (Fig. 10.7 and 10.8), local aeration and feeding system (Fig. 10.9), split-pond (Fig. 10.10), fish cage in a pond (Fig. 10.11 left), etc. These land-based intensive aquaculture systems are popular with conventional producers.

The greenhouse shrimp farming in cement pond and filter-feeding bivalve farming in earthen pond have been integrated to realize the two system complementation in some regions in China. The inflow of high-density microalgal tail water from shrimp ponds into shellfish ponds not only solves the issue of tail water treatment of shrimp ponds, but also solves the fertilization issue of shellfish ponds. It should be an important development direction for land-based intensive aquaculture systems to realize the complementation of different land-based farming systems.

The carbon footprint of land-based intensive aquaculture systems will gradually decrease in the future as the proportion of non-fossil energy in total energy consumption increases. As each country becomes carbon neutral, aquaculture production will also become carbon neutral. Therefore, whether the production costs can be reduced is the key to the eventual adoption of a land-based intensive aquaculture system.

Brief Summary

1. Land-based intensive aquaculture systems include recirculating aquaculture systems, solar recirculating aquaculture systems, raceway aquaculture systems, and biofloc-based aquaculture systems.
2. Recirculating aquaculture systems (RAS), also known as industrial aquaculture systems, are tank-based closed-loop aquaculture systems in which aquatic organisms can be cultured at high density under controlled environmental conditions. The 'wastewater' or 'tailwater' is treated and recycled with mechanical filtration, biofiltration, disinfection, temperature regulation, oxygen supply, etc. RASs have advantages including: less water consumption, less pollutants discharge, less space occupied, high yield and predictable harvesting schedules, traceable products, etc.
3. The aerobic environment of conventional RAS makes the denitrification in the system negligible, and the aerobic biofilter only changes NH_4^+ into NO_3^-, and the total dissolved inorganic nitrogen will accumulate in the system. Modern RAS introduce denitrification by microorganisms into the system. The denitrification unit reduces NO_3^- and NO_2^- to N_2 under anaerobic conditions, which eventually escapes from the RAS system, avoiding the accumulation of inorganic nitrogen. RASs with denitrification function still have the problem of high energy consumption.
4. Solar recirculating aquaculture systems (SRAS) are the systems that implant aquatic plants (submerged or floating or emergent plants, or phytoplankton) into RASs, which have lower cost of water treatment than that of conventional RAS.
   - Aquaponic system (APS) is a combination of conventional RAS and hydroponics, implanting emergent plants or floating plants or submerged macrophytes into a recirculating aquaculture system. APS takes advantage of the mutually beneficial effects of fish and plants fully. The implanted plants absorb and remove excess nutrients from the water environment, achieving the goals of water purification, effluent reduction, and economic benefit increment.
   - Compared with the APSs based on emergent plants or floating plants the systems based on submerged macrophytes can absorb CO_2 from the water and release dissolved O_2 into the water.
   - The SRAS based on phytoplankton is the aquaculture system that integrates a high-rate algal pond (HRAP) to treat RAS effluent.
5. Raceway aquaculture systems are the aquaculture systems that form high water flow in relatively shallow waters in order to sustain aquatic organisms. Raceway aquaculture systems include flow-through raceways, loop raceways, and in-pond raceways. Compared with ponds, raceway aquaculture systems have several advantages, such as electricity power energy saving, high production per unit of

space, easy to manage, high feed utilization, less even zero discharge of organic matters, and easier to implement multi-species and multi-specification culture according to market demand.

- Flow-through raceway aquaculture systems are often found in mountainous or hilly areas with sufficient gradient, where creeks or springs flow by gravity through earthen ponds or concrete tanks connected in series.
- Loop raceway systems are equipped with water pushing devices, which can drive the water flow in the loop raceway. The outdoor systems are commonly used to culture phytoplankton, while the indoor systems are often used to culture fish, shrimp, etc.
- In-pond raceway system (IPRS), also known as in-pond recirculating aquaculture system, is the combination of traditional raceway system and pond aquaculture system. The IPRS is a paradigm of partial intensification of traditional aquaculture system. A complex IPRS in a pond consists of a flow-through raceway area, a faces and residual collection area, a mollusk rearing area, and an aquatic plant (seaweed) plantation area, thus achieving a step-by-step utilization of input feeds.

6. Biofloc-based aquaculture systems are culture systems based on the concept of heterotrophic food webs, and are now widely used to culture tilapia and shrimp that can directly utilize natural productivity. The advantages of the systems include: less energy consumption, no or less high-protein feed required, water savings, good prevention of shrimp epidemics, zero pollutant discharge, and land savings.
7. The main ecological processes affecting the water quality of biofloc aquaculture system include photosynthesis, heterotrophic assimilation, nitrification, and denitrification. Since the C/N of heterotrophic bacteria is higher than that of high-quality feed, the C/N of the water should be increased by applying organic carbon sources or using low protein content compound feeds. Since both nitrification and heterotrophic assimilation consume great amount of bicarbonate, alkaline compounds need to be applied to the water frequently to stop the significant drop in pH of the water.