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REVIEW

REVIEWS IN Aquaculture

The future of intensive tilapia production and the circular bioeconomy without effluents: Biofloc technology, recirculation aquaculture systems, bio-RAS, partitioned aquaculture systems and integrated multitrophic aquaculture

Sergio Zimmermann[1] | Anders Kiessling[2] | Jiasong Zhang[3]

[1]R&D, Zimmermann Aqua Solutions, Sunndalsøra, Norway

[2]Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences, Uppsala, Sweden

[3]South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Guangzhou, China

Correspondence
Anders Kiessling, Department of Animal Nutrition and Management, Swedish University of Agricultural Sciences, P.O. Box 7024, Uppsala 750 07, Sweden.
Email: anders.kiessling@slu.se

Funding information
Swedish University of Agricultural Sciences

Abstract

Modern tilapia farming with low use of water aims, as in circular bioeconomy, to reduce inputs and fully reuse waste and effluents, closing flows or links of economic and ecological resources and decentralizing production systems (local production and local consumption). Concerns over diseases, market demand for a clean, sustainable and ecologically correct aquaculture, with greater and more efficient controls, increased predictability and repeatability of activities, are leading to a series of structural changes in the reuse of water and effluents through various closed recirculation systems with the reuse of waste as nutrients. In recent decades, one of the most important innovations and trends of tilapia culture is towards circular bioeconomy, characterized in this review by several recirculation systems, such as biofloc technology (BFT), recirculation aquaculture systems (RASs), bio-RAS, partitioned aquaculture systems (PASs with split ponds, SPs; and in pond recirculation system, IPRS) and integrated multitrophic aquaculture (IMTA). The future of tilapia culture meshes with urban agriculture and waste fermentation, where low-demand water recirculation systems will be the protagonists in the disruption of industries in five main sectors (materials, energy, information, transport and food/health), that still today focus on extraction, into a more sustainable local model.

KEYWORDS

bioflocs, bio-RAS, circular bioeconomy, culture systems, recirculation, tilapia, zero effluents

1 | INTRODUCTION

Resource flows in a circular economy can help reduce the use of increasingly scarce resources, reduce waste production and limit energy consumption. In a world with a growing demand for clean water and healthy food, the economy in a linear model is no longer adequate, since modern societies cannot build a future under a 'take-do-discard' model. The movement towards environmentally sustainable systems is necessary through circular and life cycle thinking to preserve our finite natural resources.[1–4] Water, in particular as a valuable resource, must be treated with respect and managed with methods to reuse and conserve it, putting into action the concepts of circular bioeconomy.

2 | CIRCULAR BIOECONOMY WITHOUT EFFLUENTS

The circular economy can be defined as a production strategy that aims to reduce inputs, as well as waste production, closing economic and ecological resource flows or links, decentralizing production systems (local production and consumption) and questioning tools for measuring economic performance and the role of money and finance in building natural and social economic capital.[3] The analysis of physical resource flows is of two main types: (1) linear, where biological wastes (nutrients) are expected to be reintroduced into the biosphere and (2) circular, with biological wastes (nutrients) being recirculated and used again in the production system, not returning to the biosphere. Traditional aquaculture generates wastes deposited directly into nature, providing high levels of nitrogen and phosphorus to the natural environment. These represent a threat to human health, the welfare of fish and shrimp and the overall environment.[1] The frequent diseases that occur in aquaculture and the growing demand of the population for clean, sustainable aquafarming that is environmentally friendly are leading to the development of alternative production models with greater and more efficient controls, increase in predictability and repeatability of activities. These include a series of structural changes in aquaculture activity that consider the treatment of water and waste through closed land-based recirculation aquaculture system (RASs) and the reuse of wastes as nutrients. The partial or total reuse of water from aquatic crops has generated a series of land-based RAS, undoubtedly the most important innovation in aquaculture in recent decades when integrated with complementary systems forming a donor and receiver system.

Recirculation is based on the water movement through various compartments, tanks or ponds of different sizes. The water passes from one compartment to another and is partially or totally reused, depending on the intensity of the culture, ranging from more extensive/semi-intensive ponds to intensive/super-intensive tanks. The more intensive systems make use of sophisticated biofilters, compartments with biofilters, mechanical filters, geo-membranes/liners and various treatment methods, using any species grown in conventional aquaculture such as fish, crustaceans, molluscs, algae, and so on. Recirculation technology is widely used today in tropical fish farms, primarily for biosecurity reasons. RAS is showing enormous growth in marine shrimp, bivalve and seaweed farming, especially in the initial phases (hatchery and nursery). There is also enormous investment in recirculating water in salmon farming, but at low temperatures filter microorganisms are not very efficient, which greatly increases the costs of biofilters and additional structures.

Low water demand systems, either in isolated or recirculating compartments with intense aeration and high load of omnivorous tilapia or shrimp (more than 8 units/m^3 for fish and 100 units/m^3 for shrimp) end up spontaneously generating bioflocs.[5] In a single compartment, for example, a pond or tank, bioflocs are known as BFT (from biofloc technology). By recirculating the water in more compartments, this system can be called bio-RAS, a combination of the BFTs with the RAS, a term originally coined by Prof. Anders Kiessling back in 2015.[6] The primary objective is to improve the biosecurity of crops in places where water is scarce and/or land is expensive since the minimum exchange of water reduces the incidence of diseases.[7] The recirculation and reuse of water is the most classic application of the circular economy in aquaculture. These techniques are deployed in several aquaculture systems with possibilities of 'zero effluents' (Figure 1), whose focus is to maintain stable water quality and levels, suitable through the recycling of nitrogenous and carbon components, carried out mainly by specific bacteria, which are stimulated by the balance/ratio of carbon and nitrogen (C:N) in the water. The structure of this review is based on a publication prepared by the first author and collaborators for EMBRAPA/Brazil.[8]

3 | RECIRCULATION AQUACULTURE SYSTEMS

Recirculation aquaculture system technology has been developed over the last five decades, and it is becoming more popular and accessible as infrastructure and equipment are proportionally decreasing in price, while fish, labour and especially feed are increasingly expensive. Apart from that, RAS are being well applied in grow-out systems that are extensive in nature (in order to save water, increase yield and lower production costs) and intensive systems (on high-cost property, closer to urban markets and where water is expensive).[8] The main objectives of a more extensive RAS in ponds are to conserve water and generate less effluent that could damage the surrounding environment. To achieve this, an increased technology level is needed, by default increasing productivity. Despite the productive and environmental advantages, the reuse and maintenance of water quality, especially in more intensive RAS, will depend on a series of structures and equipment that are still relatively expensive, such as: settlers, mechanical filters, biological filters, ultraviolet lamps (disinfection), water pumps, air blowers, power generator, emergency aeration, ozone generation, and so on. (Figure 2). In addition to the high investments in building structures and equipment, there are high operating costs such as electricity, maintenance and depreciation. This is in part compensated for by the flexibility to locate production facilities near large markets, complete and convenient harvesting, quick and efficient disease control.[8] RAS have been widely used for hatcheries and nurseries for both freshwater and marine aquaculture. In recent years, large scale production with RAS for grow-out to harvest size have come into commercial success. Unfortunately, there were a significant number of failures of RAS commercial operations before the more recent successes.

4 | BIOFLOC SYSTEMS

Bioflocs are usually formed in isolated compartments (tanks or ponds),[8] but, unlike high technology water purification used in RAS, water recycling occurs directly in the fish production unit, reducing the size and the cost of mechanical and biological pipes, pumps and filtration systems. The process is somewhat similar to an activated

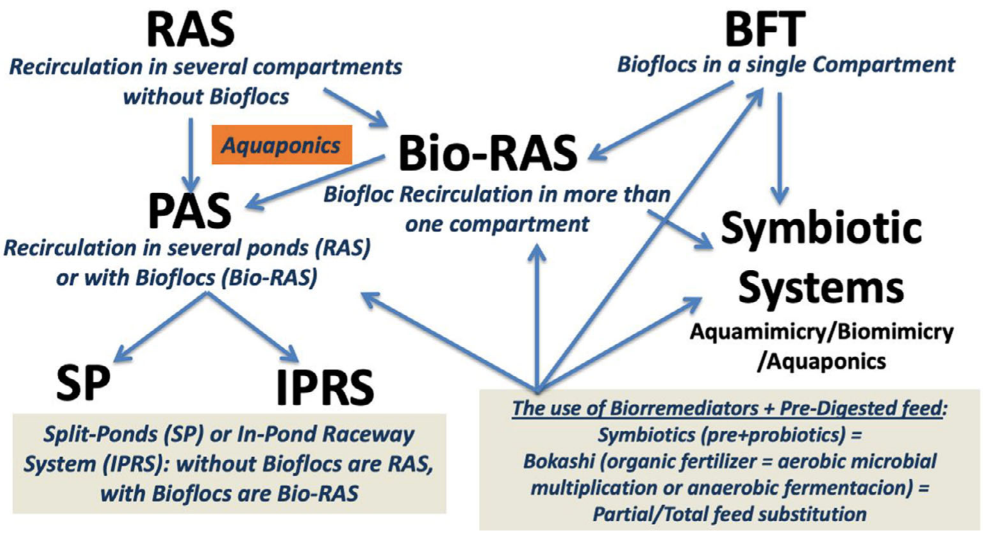

FIGURE 1 Characterization of the main aquaculture systems with low demand for recirculating water without effluents and their various derivations.

FIGURE 2 High technology and clear water recirculation aquaculture system for Tilapia (www.globalfish.pl).

sludge system used for wastewater treatment. The bioflocs are composed of assemblages of heterotrophic, nitrifying and cyano-bacteria as well as various algae and fungi. Therefore, compared with the more intensive RAS, it does not require filtration structures and can simply consist of tanks and aerators/pumps (Figure 3). The BFT can be inserted into a recirculation system (optional), with settler (optional) to control excess solids, drainage system (optional), blower and/or water pump and power generators. The structural and operational advantages of a BFT allow cultivation with high loads of suspended solids in the water, characteristics that affect different species produced in the RAS, but do not impact omnivorous filter-feeding species such as tilapia and marine shrimp, two of the most used species in BFTs around the world.[8] The ability to work with a relatively high solids load makes the BFT less dependent on mechanical filters.[6] It also abolishes the need for either partial water exchange or a secondary denitrification system typical of a highly intensive RAS. Some microorganisms that grow in the bioflocs of the culture water, such as nitrifying bacteria, transform toxic nitrogenous compounds (mainly ammonia and nitrite) to nitrate, also eliminating the need for an external biofilter, mandatory in recirculation systems (RAS). In essence, toxic ammonium is assimilated to organic N by heterotrophic bacteria and algal biomass when carbohydrate is added into culture water,[9] and thereby also function as an additional feed source for the farmed fish/shrimp. Such systems require constant and reliable aeration and physical water movement equipment in order to keep sediments suspended, plenty of available dissolved oxygen and avoid anaerobic sludge accumulation. In addition, careful monitoring and manipulation of dissolved oxygen, alkalinity, pH and C:N ratio is required.[5]

FIGURE 3 BFT (system without water exchange) in a greenhouse, with constant temperature throughout the year, in the sub-tropics of Brazil. *Photo*: Rafael Jung (2002).

FIGURE 4 Bio-RAS with six greenhouse fattening reactors, recirculation tank (bottom) and denitrifying tank or sludge concentration/reuse tank (top left). *Photo*: Sergio Zimmermann (2003).

5 | BIO-RAS

Bio-RAS is the combination of RAS with BFT (a recirculation system with bioflocs in more than one compartment).[8] The advantages of BFT over classical RAS became apparent three decades ago, when different systems based on bioflocs were developed. Currently, there is a trend to merge these two low water demand systems to optimize crops with a reduction in production costs (especially food and electricity). The bio-RAS strategy uses the best and most efficient of each of the previous technologies, with cost reduction combined with the maximization of technological, zootechnical and animal welfare efficiency with the sustainability of the crops.[6] Bio-RAS has been used in the last decade in a number of low-cost aquaculture projects (Figure 4). In bio-RAS, bioflocs can form in part of one or more compartments, or of the entire circulating water (in this case, it requires some adaptations in the filtration system or its exclusion).[8] In most

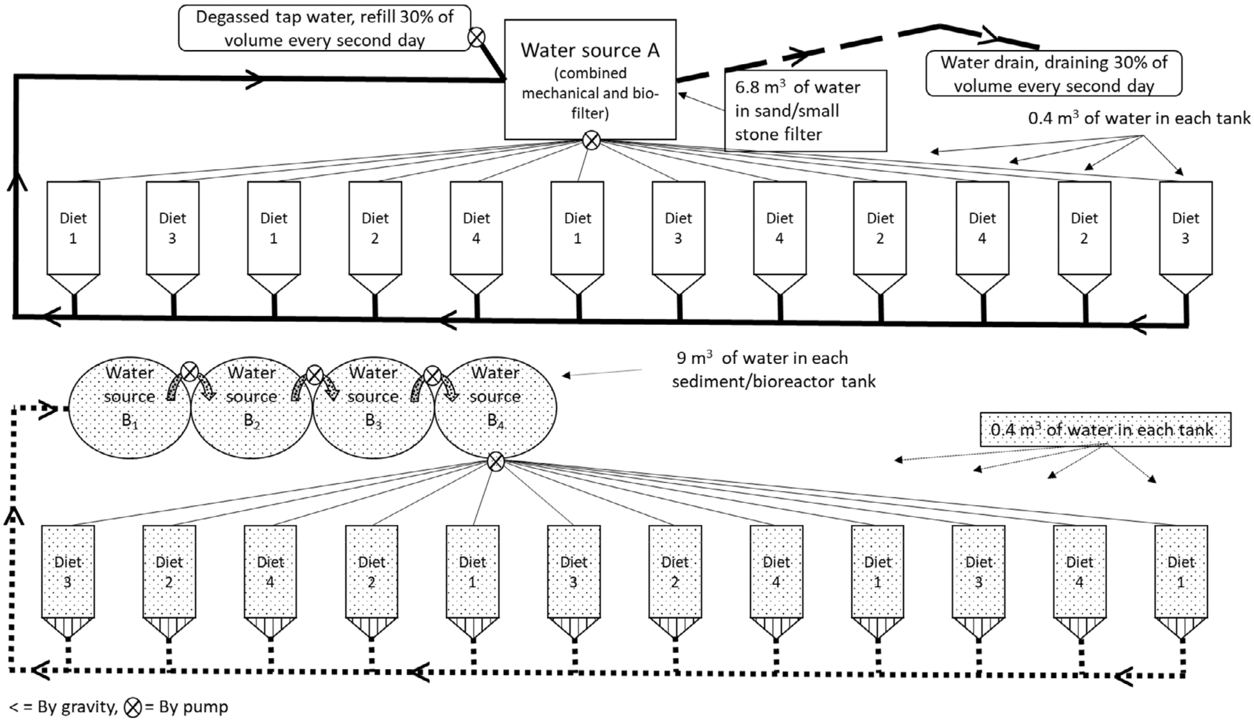

FIGURE 5 A simplified drawing of the CW- and bio-RAS systems used by Kiessling and co-workers[6] at AnGiang University in Vietnam. Extracted from Reference 10.

cases, it is part of the sludge reuse system of a simplified RAS, without effluents (Figure 5 shows a simplified drawing of the CW- and bio-RAS systems used by Kiessling and co-workers at AnGiang University in Vietnam).[6]

6 | PARTITIONED AQUACULTURE SYSTEMS

The partitioned aquaculture system (PAS) was developed in the 1990s in the southern United States to cultivate American channel catfish with recirculation of wastewater. The objective is producing zero effluents,[11] where fish are confined in high densities in concrete tanks (raceways) or smaller channels/ponds, around 5% of the total area for the tank and 95% of the pond or lake for recirculation and reuse of water. The fish residues from its catabolism circulate and recycle through the water body where there are high concentrations of algae (fertilized by these residues), similar to a domestic wastewater treatment, which increases or even doubles the support capacity of the system. By doubling the rate of photosynthesis of algae in these generally isolated baffles and ponds, the rate of removal of nitrogenous, phosphorous and other waste products doubles, thus doubling the potential maximum feeding rate and the consequent carrying capacity to sustain the system and the fish and shrimp production.

PAS represents a high degree of intensification for previously extensive ponds and reservoirs where phytoplankton predominate.[11] In its various forms, productions in the range of 10–50 tons of tilapia per hectare of surface or 10,000 m^3 of total volume are obtainable. Its two main variations are increasingly common around the world: (a) *IPRS* for in pond raceway system with a pond/reservoir/lake holding cages, raceways or containers (Figure 6a–f) and (b) *SP*s for split ponds (Figure 7).

IPRS confine omnivorous fish at high densities in cages or raceways (channels with high water flow) installed along the inside periphery of an existing lake or pond. The water recirculates through the large bodies of water that assimilate the waste from the small, cultivated areas, facilitating the feeding, sampling, protection and harvest of the fish.[11] Although IPRS was originally designed for channel catfish aquaculture in the southern United States, its use expanded and became more popular in the farming of carp, tilapia and other omnivorous fish in China, India, Brazil, Colombia, Thailand and several other countries.[8]

The SP's also originated in the southern United States, taking advantage of the huge dams with reservoirs available as a starting point for the construction of the system. SPs are built by dividing a fish pond into two unequal sections by building a central partition or dike, with water circulating between the two sections with high-volume, low-head pumps. Compared with the IPRS, SPs usually have a relatively smaller recirculation basin (around 80%–85% of the total area) and a larger fish retention basin (15%–20% compared with 5% of the IPRS). In both systems, farmers are increasingly using pumps connected to solar collectors to reduce electricity and electrical installation costs.[11]

Some PAS adopt techniques derived from bio-RAS, with early research and scientific publications using bioflocs as biological water treatment in large-scale commercial systems for intensive fish and

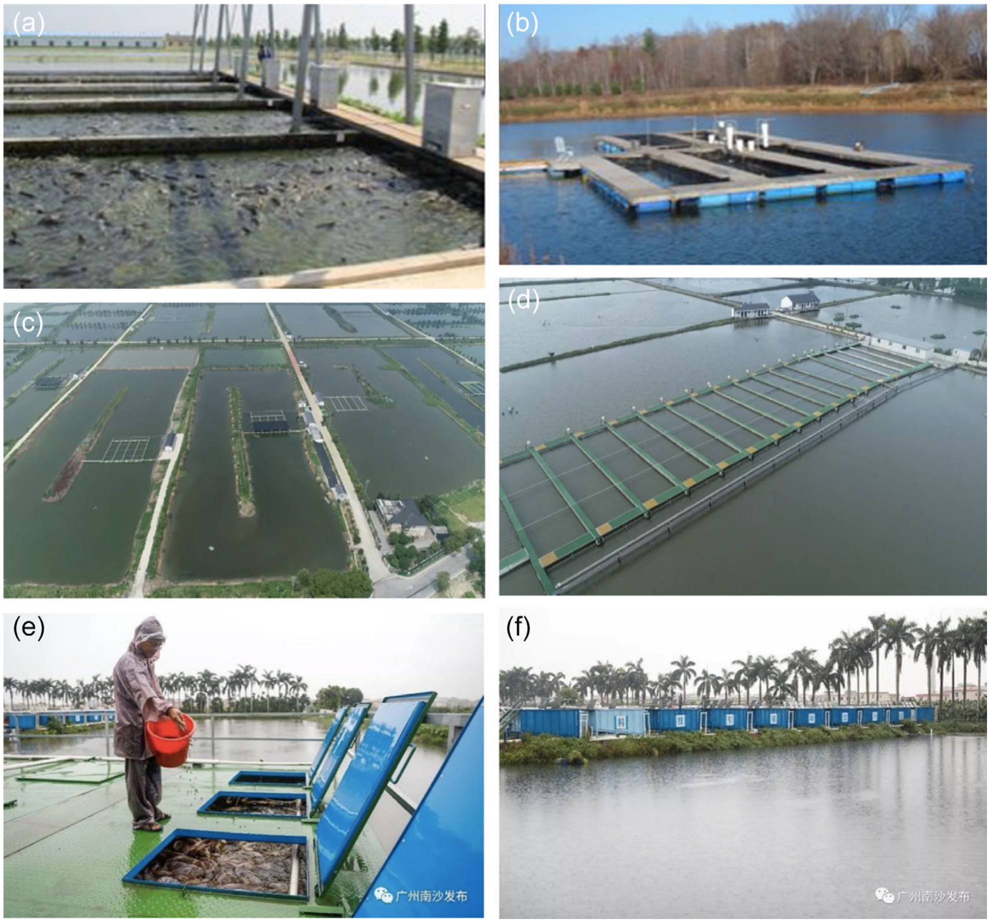

FIGURE 6 Raceways on the banks of a pond or lake (IPRS), floating cages inside a reservoir, IPRS in a typical RAS pond farm and Tilapia being cultured in containers on the banks of an earthen pond used as a purification system. *Photos*: Sergio Zimmermann and Chinese Medias (2021).

shrimp production. At higher densities, PAS change rapidly to a predominance of bioflocs and require more and more aeration, water movement and the addition of symbiotic supplements (pre +- probiotics) as summarized in Figure 1: Bokashi (organic fertilizer/bioremediator), fermentative Premix (FermentAqua®), EM (Enhanced Microorganisms) or mixotrophic products (BlueAqua's Mixotrophic System®), and so on. These have been developed into a series of systems, among which are aquamimicry heterotrophic, autotrophic, photo-autotrophic and the active suspension system, various techniques which use concepts generated in the RAS and BFT systems mixed with bio-RAS.[5,6,8]

7 | INTEGRATED MULTITROPHIC AQUACULTURE (AQUAPONICS AND FERTI-IRRIGATION)

In integrated multitrophic aquaculture system (IMTA), two or more complementary species with different trophic levels or niches are farmed. For example, tilapia with shrimp and seaweeds in brackish water. Another example would be tilapia, silver carp and water lotus in freshwater. In some cases, fish and terrestrial animals and/or hydroponics (vegetables) could be in the same production system in recirculation with single or multiple loops. The integration between aquatic and terrestrial species (such as plants, pigs, poultry, among others) is maintained with multiple relationships between resources (such as space, water, food or nutrients). Generally, these are shared between different species, thus offering greater potential in terms of technical and economic efficiency and redundancy.[12] In the past, the production of more than one aquatic species in the same culture unit, either in earthen ponds or in cages, was called polyculture, while aquatic and terrestrial organisms that were produced together, was called integrated aquaculture (IA). In IA, the waste output from one subsystem generally becomes an input for another subsystem, resulting in greater efficiency in the production of aquatic organisms.

IMTA combines the cultivation of fed species (e.g., tilapia + shrimp) with extractive (species, grazers and filter feeders) feeding on organic matter (echinoderms, molluscs, especially bivalves, micro-crustaceans and worms, other herbivorous fish) and inorganic extracting species (such as phytoplankton and marine macroalgae or hydroponic vegetables). The goal is to match in the right proportions to create balanced systems that generate environmental and economic sustainability and social acceptability. The feeding costs of the IMTA systems are thus distributed between two or

FIGURE 7 Aerial view of split-ponds or split ponds/weirs (partitioned) from the Google Earth program (accessed in August 2020). *Photo*: Sergio Zimmermann.

FIGURE 8 Uncoupled aquaponics system, tilapia juveniles integrated to the production of mini-tomatoes in ferti-irrigation and vegetables in hydroponic profiles. Collection and storage of rainwater (left outside), in the extreme south of Brazil (sub-tropics). *Photos*: Fagner Tafarel Campos de Sá (2021).

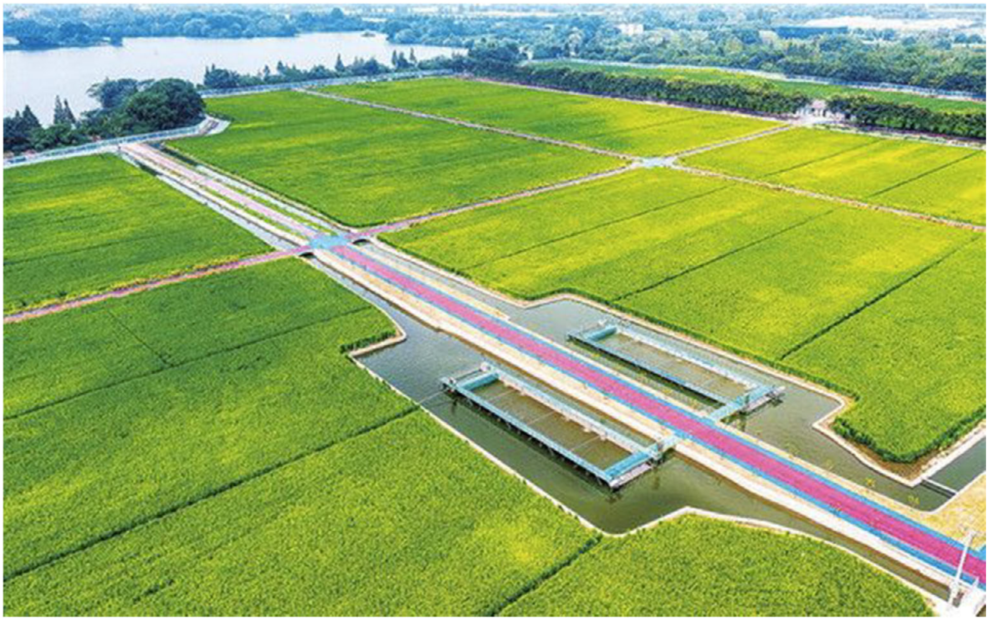

FIGURE 9 Integrating IPRS with rice production in China (2020). *Photo*: Chinese Medias (2021).

FIGURE 10 Tilapia and rice culture in China (2021). *Photo*: Chinese Medias (2021).

more commercial crops where more nutrients can be captured and sequestered, avoiding the loss of valuable inputs. Therefore, IMTA can produce more than one type of edible crop from feed ingredients more efficiently than other conventional production systems. For example, in an integrated system of tilapia with shrimp and hydroponics (aquaponics) with fertigation, the metabolites produced by aquatic organisms serve as nutrients for each other and for plants (Figure 6c–e). In addition, the sludge from RAS and bio-RAS systems can be reused as pre-digested ingredients (highly digestible) in rations for aquatic and terrestrial animals (Figure 8a–c).

Aquaponics is one of the classic examples of IMTA, an interaction between hydroponics and aquaculture, where one crop benefits from the by-products of another, making the respective ecological 'bottlenecks' of both systems become strengths, considerably reducing the need for inputs, nutrients and effluent production, unlike when the same systems are run individually.[13] Aquaponics systems can be important tools to enable economic temperature control, disease prevention, predator control and the full use of the most expensive inputs (rations) and should also be encouraged for their sustainability and biosecurity characteristics (Figures 9 and 10).[14]

8 | COMPARING THE SYSTEMS

In 2021, the Brazilian Ministry of Agriculture published a booklet with the main characteristics and production costs of several tilapia intensive rearing systems,[15] such as BFT, bio-RAS, ponds and cages from the States of São Paulo and Paraná (subtropical climate). The authors stressed that the comparison between technologies should go beyond observation of the production costs per ton of tilapia. It is very important to evaluate the Capital Expenditure/Operational Expenditure (CAPEX/OPEX), and especially the increasing land costs (not considered in the study, thus favouring the more extensive systems such as IPRS and SP), as well as water volumes and the annual production potential of each technology. This last feature altered the financial

TABLE 1 Characterization of the main tilapia aquaculture intensive recirculation systems with low demand of water and effluent production

Culture system	Grow-out volume (%)	Recirculation volume (%)	CAPEX (USD/kg/year)	OPEX (USD/kg/year)	Productivity (kg/m^3/year)	Prod. cycle (days)	Average FCR	Required area (ha) per 100 Mton/year	Profitability index (%)	Levelling point (in kg)	References
BFT	100%	–	2–8	1–2	20–30	120–140	0.9–1.25	0.4	11.22	55,680	5,8,10,15–17
RAS	80%–90%	10%–20%	6–20	3–8	30–50	120–150	0.95–1.30	0.25	4.35	–	5,8,10,15–17
Bio-RAS	50%–80%	30%–50%	3–8	1–1.5	30–40	100–120	0.75–1.20	0.3	24.81	55,895	5,8,10,15–17
SP	20%	80%	1–3	0.5–1.5	5–10	180–210	1.10–1.60	0.6	46.05	53,295	5,8,16–18
IPRS	1%–10%	90%–99%	3–5	1–3	4–6	180–210	1.25–1.75	1	6.05	227,452	8,16–18

Note: Typical grow out/recirculation rates, CAPEX/OPEX per kg annually produced, productivity, FCR, required area, profitability index and levelling point.

result and may favour one or another technology. This is the case of BFT and bio-RAS, which could perform 2.6–3 cycles per year, with the financial differential of low water requirement production technologies, where management efficiency should reach high levels to the systems to be viable, as well as the appeal to be environmentally sound. This study was later published in more detail with a short economic analysis,[16] and it is summarized together with other references characterizing the systems in Table 1.

It is very challenging to summarize quantitative data on nutrient flows or balances when describing most extensive systems such as RAS in ponds or PAS (SP or IPRS).[18] Table 1 summarizes information on how the dimensions of the grow-out and 'purifying/receiving' (recirculation) water bodies (tank, pond or lake) are applied worldwide in order to generate a better understanding of how each of these main five systems are dimensioned, functioning and yielding. The ranges presented were collected in commercial structures in Brazil, Peru, Ecuador, Colombia, Mexico, USA, Thailand, Vietnam and China.[17,19]

9 | CONCLUSIONS

Tilapia culture will evolve along with the trends of food production that are increasingly urban, 'on the roofs of supermarkets' and in urban industry facilities,[20] where aquaponics and water saving/recirculation systems will be the producers in these new forms of Circular Economy.[8,20] During the COVID-19 years and more recently the war in Ukraine, it is clear the increasing disruptions of the centralized extractive industries that today sustain the global economy in the five main sectors (materials, energy, information, transport and food/health), are evolving into a more local model. It is suggested that production and process costs could decrease by an order of magnitude of 10 times by 2030, that is, we will use 90% less natural resources and produce 10 times less waste.[20]

Modern tilapia culture systems with resources flowing in a circular economy will reduce the use of increasingly scarce resources such as water, energy, labour and especially feed ingredients, minimizing waste production. Novel pre-digested dough-like feed (FermentAqua®), produced from inexpensive by-products or diet ingredients are replacing traditional diets with low cost and improvements in productivity.[19] The convergence of precision fermentation and water circularity is enabling rapidly falling costs.[20] The recirculation systems characterized in this review include: BFT, RAS, bio-RAS, PAS with SPs and IPRS and IMTA. Each system has different characteristics in term of production costs, carrying capacities, FCR, cycles per year, CAPEX/OPEX, financial characteristics, water requirements, production technologies and can be chosen based on specific situations such as land prices, market demands/distance, water availability and several other parameters.

AUTHOR CONTRIBUTIONS

Sergio Zimmermann: Conceptualization; investigation; methodology; supervision; validation; writing – original draft; writing – review and editing. **Anders Kiessling:** Conceptualization; formal analysis; funding acquisition; investigation; supervision; writing – review and editing. **Jiasong Zhang:** Visualization; writing – review and editing.

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DATA AVAILABILITY STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article. The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Sergio Zimmermann https://orcid.org/0000-0002-0393-1922
Anders Kiessling https://orcid.org/0000-0002-5325-3779
Jiasong Zhang https://orcid.org/0000-0001-9490-119X

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