NUTRIENT WASTE AND WASTE-WATER MANAGEMENT IN AQUACULTURE: STEERING CIRCULAR ECONOMY AND SUSTAINABILITY DISCOURSE

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DOI: 10.5958/2249-7137.2024.00035.5

ABSTRACT

Aquaculture based farming of fish and aquatic products are sought after source for nutritious food, capable of addressing world food security and hunger needs. Managing nutrient waste from intensive aquaculture systems is a global challenge. Moreover, continual water supply in terms of quantity and quality are key determinants for aquaculture productivity. Increase in global population and need for enough food to meet nutrition demands has put pressure on food production systems involving water and land. Sustainable water and waste management will be key drivers to future food generation. Waste generated from aquafarming applications and practices can be reutilized, recycled, refurbished by innovative approaches such as RAS, IMTA, BFT, aquaponics, microalgae use, leading to circular aquaculture outputs of improved fish yields, water quality improvement and waste valorization with value-added production.

KEYWORDS: *Aquaculture, Waste Valorization, Biofloc, IMTA, RAS, Algae, Circular Bioeconomy.*

INTRODUCTION

Aquaculture is fast growing source of quality nutrition fulfilling protein requirements of population world-over (Hua et al., 2019). Aquaculture based farming of fish and aquatic products are sought after source for nutritious food, capable of addressing world food security and hunger needs (FAO, 2018).World population is projected to rise exponentially from present 7.6 billion to 9.8 billion by 2050 with nearly 83 million births every year (UN, 2017) anticipating rise in food demand at 50 % to tend future food requirements. Increasing global population need for enough food to meet nutrition requirements is expected to put pressure on food production systems involving water and land. Thus anticipating 30 % increment in water withdrawals compared to present (Michel, 2023). Aquaculture services have become integral part of global food systems contributing largely to world population through fed and extractive species production (Verdegem et al., 2023). Water-food systems interconnections are central themes in biosecurity of aquatic system, food safety and nutrition (Ringler et al., 2022). Future growth and sustainable aquaculture development will depend on large scale integration of circular goals with economic, environmental and societal benefits.

1. Aquaculture waste-water and nutrient waste problem

Strained water supply and continual water stress in terms of quality, quantity is key determinants in aquaculture productivity potential. Culture waste-water (WW) is after-product of finfish and shellfish farming containing large amount of organic, nutrient waste, including nitrates, ammonia (NH_3), nitrites, phosphorous (P), solid suspension, minerals, chemical compounds (from fertilization, antibiotic treatments), heavy metals, and pathogens (Leong et al., 2021). Intensification of aquafarming has led to increased dependence on artificial feeds with high cost associated to maintain water quality (Henriksson et al., 2021). Feed is a significant contributor of antibiotic growth promoters to freshwater aquaculture, posing contamination risk to algae and putative human hazard (Hu et al., 2010). Overaged diets, unutilized fish feed, fish metabolites and farming waste, contribute waste nutrient accumulation in culture environment leading to eutrophication and toxic blooms, hence require apposite addressal (Ojewole et al., 2024). Improper feed disposal, fertilization of culture water and poorly stored feed are known to transfer resistance mechanism in opportunistic trains (Milijasevic et al., 2024). Ammonium (NH_4^+) and inorganic phosphorous loads can favour proliferation of pathogenic strains causing disease incidences (Olsen et al., 2017). Bacterial species *Enterobacter, Streptococcus iniae, Escherichia coli, Salmonella spp., Shigella spp. Aeromonas hydrophila*, *Staphylococcus aureus*, *Pseudomonas putida* and *Enterococcus faecalis* have been identified in infected fish species including tilapia, channel catfish, yellow catfish, grass carp (Nhinh et al., 2021; Ogbonna and Inana, 2018; Hongsen et al., 2024).

1.1 Circular economy in aquaculture

Circular economy paradigm focusses on resource reuse potential. Recycling and reutilisation of waste-by-products are pillars for circular bio economy (Venkatesh, 2022). Circular aquaculture explores circular economy goals of life cycle analysis (LCA) for environmental impact assessment, allowing closed-loop integration of waste generation and repurposing, maximizing resource use efficiency (Falcone et al., 2022). It aims at inventive technologies for aquaculture waste and WW treatment, use of seaweeds and microalgae, waste valorization, as well as deployment of state-of-art aquaculture systems (including aquaponics, biofloc technology BFT, recirculatory aquaculture systems RAS, integrated multitrophic aquaculture IMTA), refer Figure 1.

1.2 Waste-water treatment and management

Aquafarming waste generated can be reutilized, recycled, repurposed supporting objectives of circular economy (Dauda et al., 2019). Various innovative aquafarming technique shave capacity to refurbish and reutilize culture waste and waste water, these include RAS, BFT, IMTA, aquaponics besides use of microalgae and beneficial bacterial systems as probiotics integrated to innovative approach (Ojewole et al., 2024).

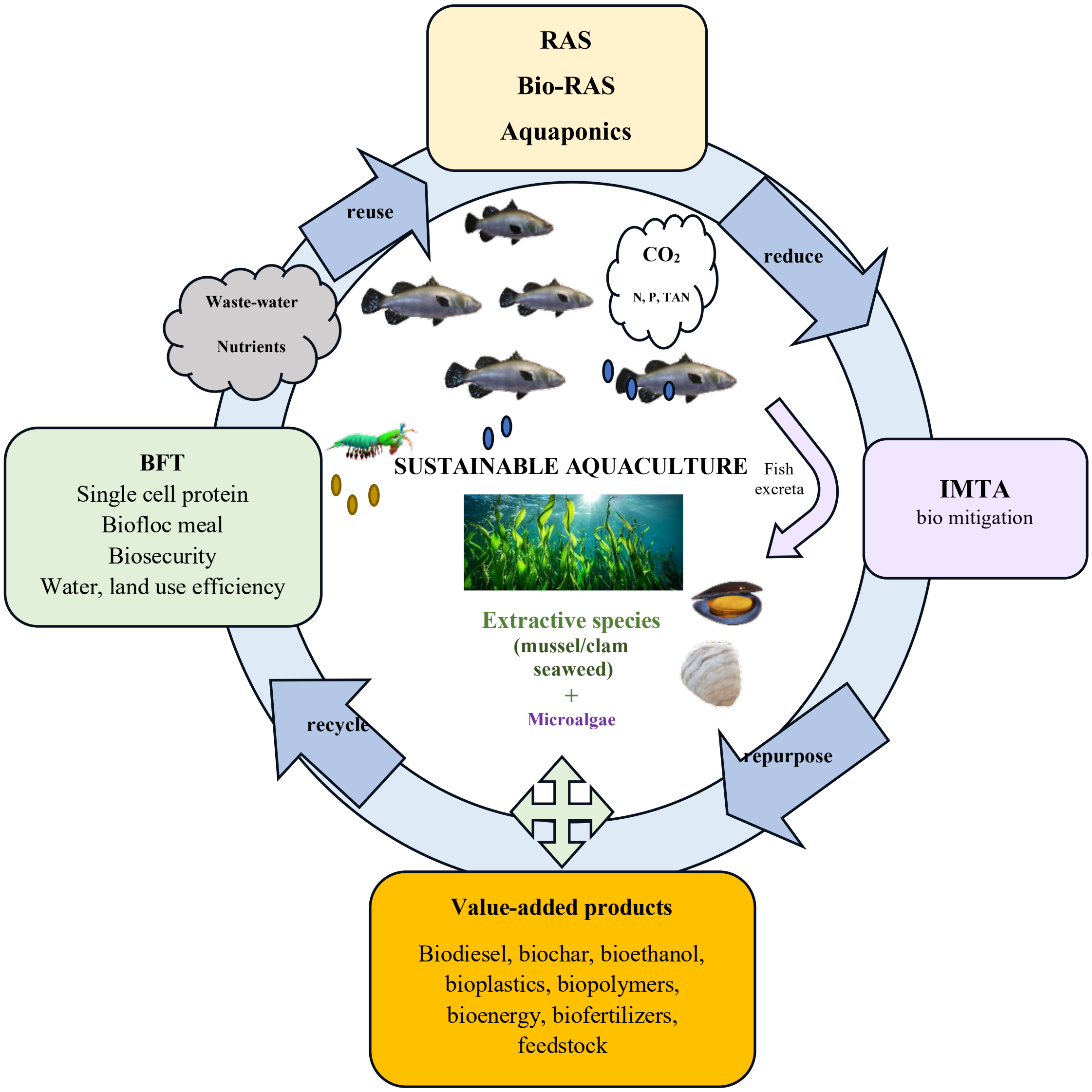

Figure 1: Circular bioeconomy goals and attainment of sustainable aquaculture development. (TAN: total ammoniacal nitrogen)

1.2.1 RAS

Recirculatory aquaculture system (RAS) is intensive, innovative farming technology that recycle, reutilizes water through mechanical and biological filtration, minimizing water exchange (Ahmed and Turchini, 2021). As an indoor closed loop culture technique RAS operates for removal of waste under controlled environment conditions. RAS system provides higher utilization rates of feed minimizing unutilized or waste feed generation (FAO and EUROFISH, 2015). Recirculation of water in RAS helps in managing culture conditions of temperature, dissolved oxygen promising sustainable aquaculture production with limited external interventions or pathogenic transmission (EU, 2020). The technique is limited by technological constraints, cost and need of skilled labor. Up to 50 percent production cost in traditional RAS is utilized in management of nutrient-rich waste-by-products (Ende et al., 2024). Recently, integrated microalgal-RAS (MG-RAS) systems have explored potential of MG-based remediation ‘phycoremediation’ of recirculating water. MG have high nutrient assimilation potential for biomass generation; capable of carbon sequestration. MG enable oxygenation of aquatic system circumventing aeration needs of culture environment.

A branch of RAS and BFT called bio-RAS is novel approach using recirculating water in multiple compartments for waste utilization (Zimmermann et al., 2023). Compartmentalization allows separate aeration, feed treatment for culture species and microorganisms circumventing contamination problems of traditional RAS. Nguyen et al., (2021) reported better feed uptake protein efficiency and growth of Nile tilapia (*O. niloticus)* in bio-RAS in comparison to traditional clear water - RAS system. Bio-RAS is a green approach for sustaining high stocking densities, minimizing water exchange and disease risk.

1.2.2 Biofloc system

Biofloc technology (BFT) is the system of use of microbial flocculation of MG, bacteria, yeast and ascomycetes to utilize remnant feed and organic detritus for manufacture of microbial biomass (De Schryver et al., 2008). Floc microorganisms source nutrients, water quality improvement and probiotic properties in farming ecosystem. (Khanjani et al., 2022b).

Bioflocs are important source of vitamins, lipids, essential amino acids in protein, carbohydrates and carotenoid substances enhancing performance parameters of farming species (Emerenciano et al., 2023). According to Ekasari et al. (2014) floc size has impact of nutritional composition and the nitrogen uptake potential of aquaculture species. Conversely, in their work Vinatea et al. (2018) described impact of cultured species on biofloc composition, with improved protein, carbohydrate, lipid content of *Mugil* fry biofloc compared to flocs for developing stages of *Tinca*. BF biomass is valuable source of single cell proteins (SCP) with potential for fishmeal (FM) replacement in aquafeeds (Dantas et al., 2016). Being highly priced protein source with excessive cost bearings FM substitution with biofloc meal is sustainable alternative for nutrient rich diets to aquaculture species. Table 1 describes nutritional benefits of biofloc to aquaculture species.

1.2.3 IMTA

Integrated multi-trophic aquaculture (IMTA) is sustainable aquaculture management approach using by-products of one culture species to deliver feed, fertilization for co-culture of other species (Rosa et al., 2020). IMTA integrates multi-trophic level consisting of *fed aquaculture species* (largely finfish and shellfish); *inorganic extractive species* (of seaweed) and *organic extractive* species of filter feeders (molluscs, clams) increasing concurrent aquaculture production (Chopin et al., 2012). Extractive species contribute ecological function of biomitigation reducing carbon dioxide (CO_2), excess P, N and heavy metals waste load (Martínez-Espiñeira et al., 2015) thus contribute to goals of circularity and sustainable productions.

TABLE 1: NUTRIENT COMPOSITION AND BENEFITS OF BIOFLOC MEAL TO AQUACULTURE SPECIES.

Species	C:N,Carbon source	Protein (%)	Lipid (%)	Carbohydrate (%)	Ash (%)	Biofloc Benefits	Reference
Pacific white shrimp (*Litopenaeus vannamei*)	15:1, molasses	28.7	2.30	ND	43	Improved antioxidant defense, innate immunity, disease resistance	Lee et al., 2017
Penaeus monodon	>12:1, molasses	47.94	5.02	29.81	1.41	Improved survival, growth, immunity	Promthale et al., 2017
Banana shrimp (*Fenneropenaeus indicus*)	8.3, 10.4 and 12.1, rice bran	18-23	17-22	51-62	3-4	Enhanced feed conversion, water quality growth performance	Megahed and Mohamed, 2014
Mugil cephalus & *Tinca tinca*	20:1, glucose (anhydrous)	17.35-17.95	1.60-2.36	7.95-19.25	ND	Increased conditional factor in *T. tinca*	Vinatea et al., 2018
		8.92	2.18	12.32	ND		
Nile tilapia (*Oreochromis niloticus*)	20:1, rice bran/coffee waste/molasses	30.28-47.99	1.96-2.50	ND	6.71-16.46	Economic cost lowered	Becerril-Cortés et al., 2018

1.2.4 Aquaponics

Aquaponics combines recirculating aquafarming (RAS) with hydroponics for concurrent cropping of fish and plant (Pattillo, 2017). In aquaponic system nutrient-enriched culture water containing fish excrements is processed by bacterial biofiltration system to support soilless plant growth. Aquaponics provide possibility of polyculture of fish increasing agro-diversity and fisheries output (Martan, 2008). Danaher et al. (2007) in their work successfully maintained polyculture of freshwater prawn (*Macrobrachium rosembergii*) with Nile tilapia (*O. niloticus*). Polyculture enable valuable production with biological control of pathogenic organisms. Additionally, growing plant crop enables economic benefit to farmers for catering off-season food demands. Estim et al. (2019) evaluated Nile tilapia aquaponic system with green beans (*Phaseolus vulgar is*) and cabbage (*Brassica rapa chinensis*) for 70 days. Efficient water remediation potential of RAS resulted in high fish survival (95 ± 2.8%), improved feed conversion rate with enhanced plant productivity. Dual-cropping, zero water discharge, and waste reutilization make aquaponics highly sustainable aquaculture system. Ekawati et al. (2021) analyzed feasibility of catfish (*Clarias gariepinus*) aquaponic system and RAS (A-RAS) in water quality and waste management. A-RAS improved water quality indicators and fish produce (13% higher than conventional system), providing water spinach as an additional economic crop to the farmers.

1.2.5 Microalgae based aquaculture waste management

Microalgae (MG) *Nannochloropsis oculata*, *Pavlova gyrans*, *Phaeodactylum tricornutum* are utilized as biofilters for waste remnants; coupling waste recycling to biomass yields under controlled environments in RAS, IMTA, BFT as circular stratagem realizing sustainable aquaculture growth (Khanjani et al., 2022a). Recently, combination of mussel-MG-bacterial system is proposed as sustainable and efficient model of aquaculture WW remediation. Mussel (*Hyriopsis cumingii*), probiotic strains of *Bacillus subtilis, B. licheniformis*, and MG *Chlorella vulgaris* were at optimal dose 4 mussels per cubic metre, 0.5 mL, 1 mL, and 2 mL respectively (Geng et al., 2022).

Nutrient-rich aquaculture wastewaters have been utilized for phycoremediation and manufacture of value-added products through cultivation of MG (Leong et al., 2021). MG's are biological refineries capable of WW reclamation, biomaterials for bioplastics, generation of bioenergy from biofuels such as bioethanol and biodiesel (Okeke et al., 2022).

1.3 Valorization of aqua waste and value-added production

Aquaculture waste valorization is the conversion of culture waste into valuable resources. Marine algae comprising MG and seaweed 'macroalgae' are important biorefineries contributing to circular aquaculture and bio-based economy (Sarma et al., 2021). Phototrophic potential of algae help sequester carbon dioxide for primary production in algal biomass lowering greenhouse gas emissions, improving aquaculture carbon footprint alongside yielding proteins, lipids, carbohydrates, pigments, valuable bioactive compounds (Levasseur et al., 2020).

Value added bioactive compounds including polyphenols, antibodies, enzymes, hormones and vitamins are obtained from aquaculture species of green (Chlorophyta), red (Rhodophyta) and blue-green alga (Cyanobacteria). Along with seaweeds, MG and cyanobacteria are valuable source of feedstock for sustainable production of aqua feeds, biofuel (bioethanol, biodiesel), bioplastics, and bioenergy (syngas, biomethane, biohydrogen) contributing to bioeconomy-based value-added production (Sarma et al., 2021; Eladl et al., 2024). Besides their role in WW treatment of culture sludge and effluents, algae assure removal of heavy metals, excessive N, P, potassium (K) loads with utilization as biofertilizers for daphnid, algal cultivation and integrated to aquaponic, biofloc system (Ammar et al., 2021).

CONCLUSIONS

Biosecurity of aquatic systems, food safety and nutrition chiefly governs growth and enhancement of aquaculture to sustainably cater world food and resource needs. Aquaculture is a fast expanding food production system with potential for improving fisheries yields using RAS, IMTA, and BFT, algal cultivation, aquaponics as closed loop technologies through generated waste-reuse, WW remediation, and recycling. Careful management of generated effluents and valorization of aquaculture waste provides large-scale opportunity for value-added production of bioactive compounds, feedstock, biofertilizers and biofuels. Essentially, repurposing of waste by products and resource recovery helps in clean water regeneration and reutilization for primary production, toxic chemical removal, supplementing sustainable development goals and objectives of biocircular blue-economy.

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