ANNALS OF ANIMAL SCIENCE
ISSN: 2300-8733, https://sciendo.com/journal/AOAS

ACCEPTED AUTHOR VERSION OF THE MANUSCRIPT:

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DOI: 10.2478/aoas-2026-0015

Moslem Sharifinia[1♦], Mohammad Hossein Khanjani[2♦]

[1]Shrimp Research Center, Iranian Fisheries Science Research Institute (IFSRI), Agricultural Research, Education and Extension Organization (AREEO), Bushehr, Iran
[2]Department of Fisheries Sciences and Engineering, Faculty of Natural Resources, University of Jiroft, Jiroft, Kerman, Iran

♦Corresponding author: moslem.sharifinia@yahoo.com (M. Sharifinia), m.h.khanjani@gmail.com, m.h.khanjani@ujiroft.ac.ir (M.H. Khanjani)

Received date: 6 November 2025
Accepted date: 3 February 2026

To cite this article: (2026). Sharifinia M., Khanjani M.H. (2026). From concept to reality: Low-carbon footprint aquaculture systems, Annals of Animal Science, DOI: 10.2478/aoas-2026-0015

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Ann. Anim. Sci., Vol. 26 (2026) 1–18 *DOI: 10.2478/aoas-2026-0015*

FROM CONCEPT TO REALITY: LOW-CARBON FOOTPRINT AQUACULTURE SYSTEMS

Moslem Sharifinia[1♦], Mohammad Hossein Khanjani[2♦]

[1]Shrimp Research Center, Iranian Fisheries Science Research Institute (IFSRI), Agricultural Research, Education and Extension Organization (AREEO), Bushehr, Iran
[2]Department of Fisheries Sciences and Engineering, Faculty of Natural Resources, University of Jiroft, Jiroft, Kerman, Iran
♦Corresponding authors:
moslem.sharifinia@yahoo.com (M. Sharifinia), m.h.khanjani@gmail.com, m.h.khanjani@ujiroft.ac.ir (M.H. Khanjani)

Abstract

Aquaculture holds great importance as a source of sustenance for the ever-expanding global population. However, it has become increasingly apparent that this industry's growth has come at a cost, as it has been linked to a range of environmental challenges, including greenhouse gas emissions. To mitigate these issues, there is a growing call for innovative and sustainable aquaculture systems capable of reducing carbon footprints. This paper examines several such systems, including recirculating aquaculture systems (RAS), integrated multitrophic aquaculture (IMTA), biofloc technology (BFT), and aquaponics. RAS is a closed loop system that recirculates water through the system, reducing the need for water exchanges and associated energy and carbon emissions. IMTA involves the cultivation of multiple species from different trophic levels within a single system, a feature that distinguishes it from simple polyculture, while enabling nutrient recycling and reducing the need for external inputs such as feed and fertilizers. BFT can minimize carbon footprints by reducing energy and water use, minimizing waste, and decreasing demand for wild caught fish as a source of fishmeal. Aquaponics marries aquaculture with hydroponics, using aquatic organisms' waste as a nutrient source for plants and reducing waste while minimizing the need for external inputs. This paper delves into the potential benefits and challenges associated with each system, along with their current status and future prospects. It also underscores the significance of technological innovation, policy support, and industry collaboration in successfully implementing these systems. In conclusion, these innovative aquaculture systems have the potential to revolutionize the industry by promoting sustainability, reducing carbon emissions, and contributing to a more resilient and equitable food system. However, a comprehensive approach that considers the economic, social, and environmental dimensions of sustainability is essential for their successful implementation.

Key words: aquaculture, carbon footprint, sustainability, recirculating aquaculture systems, integrated multitrophic aquaculture, biofloc technology, aquaponics

Aquaculture has great potential for meeting the increasing demand for aquatic food products due to population growth and economic development. With stagnant capture fishery and already overexploited resources for fish stocks across the globe, sustainable aquaculture production can supplement the animal protein demand of an ever-growing population (Costello et al., 2019; FAO, 2024; Sharifinia et al., 2023 a, b). Global aquaculture production has increased significantly over the past few decades and played a significant role in achieving the sustainable development goals (SDGs) (Bush et al., 2013; Belton et al., 2020). Notably, aquaculture can add resilience to the global food system in the face of climate change and increased demand for animal protein (Naylor et al., 2021; Khanjani et al., 2023). Aquaculture production, while essential for global food security and achieving SDGs, has significant environmental impacts and resource consumption (Emerenciano et al., 2025; Sharifinia et al., 2024). These include overconsumption of water and energy, greenhouse gas (GHG) (CO_2, CH_4, N_2O) emissions, eutrophication, degradation of aquatic, benthic, coastal habitats and ecosystems (Sharifinia et al., 2018, 2019; Jiang et al., 2022; Yuan et al., 2019). Aquaculture can under specific production conditions require higher energy inputs than certain livestock systems, for example in highly intensive recirculating aquaculture systems (RAS) land-based tank operations with continuous water pumping and aeration or shrimp hatcheries relying on energy-demanding life support equipment. These energy requirements may exceed those of comparable terrestrial livestock operations, even though low-input systems such as earthen ponds do not. In such cases, aquaculture can also contribute to the degradation of freshwater and coastal water quality (Boyd and McNevin, 2015; Troell et al., 2014; Hilborn et al., 2018). As aquaculture production continues to increase in size and resource intensity over time, its environmental impacts are likely to worsen (Jiang et al., 2022; Sharifinia et al., 2022; Khanjani et al., 2022, 2025 c). In order to tackle the challenges facing the aquaculture industry, it is becoming increasingly important to develop innovative feed technologies and sustainable systems that can help to reduce the carbon footprint of production (Naylor et al., 2021; Li et al., 2024; Sharifinia, 2025; Sharifinia et al., 2024, 2025 a, b). Carbon footprint refers to the total GHG emissions associated with a product or activity, with emphasis on direct anthropogenic emissions. Although CO_2 is often cited in general definitions, in flooded aquaculture systems such as earthen ponds, most CO_2 fluxes originate from short-term biogenic cycling and are therefore not typically classified as anthropogenic emissions. Consequently, CH_4 and N_2O, both potent greenhouse gases with clear anthropogenic pathways in aquaculture, are more relevant indicators for assessing direct emissions in carbon footprint analyses. In aquaculture direct emissions arise mainly from pond sediment processes, manure or organic load decomposition, and nitrogen transformations, while indirect emissions stem from off-farm activities such as feed production, energy generation, transportation, and infrastructure manufacturing (FAO, 2018; IPCC, 2014).

Understanding this distinction is essential because the overall carbon footprint of aquaculture varies across species, production systems, and geographical regions (Alonso et al., 2021; Li et al., 2024). To mitigate both direct (CH_4, N_2O) and indirect emissions, innovative production strategies are being developed that reduce energy demand, optimize feed use, minimize waste generation, and enhance nutrient recycling. Such advancements contribute to lowering the carbon footprint of aquaculture systems and support the transition toward circularity and sustainability in resource dynamics (Zhang et al., 2024; Das et al., 2023).

Therefore, the aim of this study is to investigate innovative and sustainable aquaculture production systems that have the potential to reduce carbon emissions and promote long-term sustainability. By identifying and promoting such systems, this study aims to contribute to the development of a more sustainable and environmentally friendly aquaculture that can reduce the carbon footprint of the industry. These systems, including recirculating aquaculture systems (RAS), integrated multitrophic aquaculture (IMTA), biofloc technology (BFT), and aquaponics are highlighted because they represent some of the most thoroughly studied and empirically validated approaches for reducing the carbon footprint of aquaculture. Extensive literature demonstrates their capacity to enhance nutrient recycling, lower reliance on external inputs such as feed and fertilizers, improve energy use efficiency per unit of biomass produced, and reduce direct emissions of CH_4 and N_2O through optimized system design and waste management. Moreover, these systems are among the most feasible and widely recommended models for broader adoption due to their proven performance in diverse geographical and production contexts, which justifies their selection as representative low-carbon aquaculture systems in this study.

Recirculating aquaculture systems (RAS)

RAS have the potential to enhance cleaner fish/shellfish production through environmental control, which can improve efficiency in environmental management. RAS provide a controlled environment for quality fish production by reducing environmental risks (Hashmi et al., 2025). Environmental control can minimize risks associated with environmental variables and their impacts. By maintaining water quality through proper management of inflow water, RAS can effectively minimize and control risks associated with disease outbreaks and parasite infestation (Ahmed and Turchini, 2021). These advantages apply primarily to indoor RAS, where systems are fully enclosed and biological access from the outside environment is prevented. Indoor RAS experience minimal predation pressure and very low escape risks and outdoor RAS installations may still be exposed to certain predation and intrusion challenges. Nevertheless, RAS have reduced risks of disease transmission to wild fish populations, as escapees are unlikely and effluent water can be treated prior to discharge (Halim et al., 2025). Moreover, RAS are free from predators due to the closed system operation, which helps to avoid the transmission of diseases and parasites from these vectors. RAS can reduce the dependency on antibiotics and other therapeutants by preventing disease outbreaks (Murray et al., 2014). Studies have shown that the carbon footprint in RAS can be high, with estimates of up to 27 kg CO_2eq/kg live weight cod in Spain and 28 kg CO_2eq/kg live weight salmon in Canada (Badiola et al., 2018; Ayer and Tyedmers, 2009). In the USA, the average carbon footprint for RAS-farmed salmon is estimated to be 7.01 kg CO_2eq/kg live weight, which can be reduced to 3.73 kg CO_2eq/kg live weight by using renewable sources of energy such as hydropower electricity (Liu et al., 2016). In comparison, pond aquaculture has significantly lower emissions with estimates of 1.37 kg CO_2eq/kg live weight of striped catfish in Vietnam, 1.58 kg CO_2eq/kg live weight of Nile tilapia in Bangladesh, and 1.84 kg CO_2eq/kg live weight of carps in India (Robb et al., 2017). This highlights the significant environmental impact of RAS in terms of GHG emissions compared to other aquaculture practices. Although air-driven rotating biological contactors in RAS can reduce CO_2 concentrations by 88.39%, more research is needed to evaluate the wider application of this technology. RAS have been criticized for their environmental impact due to high

energy consumption (Chiquito-Contreras et al., 2022). However, the use of renewable energy sources can help mitigate this issue and make RAS more sustainable. Research has shown that incorporating renewable energy sources, such as solar power, can significantly reduce energy consumption in RAS and reduce the industry's carbon footprint (Fuller, 2007). For example, a microaerophilic assimilation reactor can lower energy consumption to 7.72 kWh/kg with a stocking density of 80 kg/m^3 (Yogev and Gross, 2019). Furthermore, innovative technologies and increased utilization of renewable energy can further improve RAS's energy efficiency (Badiola et al., 2018). This not only reduces the environmental impact of the industry but also lowers operational costs. Overall, adopting renewable energy sources in RAS can play a crucial role in promoting sustainability in the aquaculture industry (Zhang et al., 2023). It is important to consider more than just direct GHG emissions when evaluating the environmental impact of aquaculture. Land use change, such as converting paddy fields to aquaculture in China, can significantly increase GHG emissions, with estimates ranging from 8.15 to 28 tons CO_2eq/ha (Yuan et al., 2019). Similarly, transforming mangroves to shrimp farms in Brazil can result in the release of 1390 tons CO_2eq/ha, which is equivalent to 182 years of soil carbon deposits (Kauffman et al., 2018). In contrast, RAS have a limited land footprint and can be implemented in a variety of areas, including unused civil/industrial areas, without major land use change. Additionally, RAS located in close proximity to markets can significantly reduce CO_2 emissions associated with natural habitat destruction and fish transportation. For example, the carbon footprint for salmon production in RAS close to a US market is half that of net-pen salmon production in Norway, which involves shipping fresh salmon to the same market by airfreight (Liu et al., 2016). In summary, land use change can significantly increase the environmental impact of aquaculture, but RAS have a proportionally limited land footprint and can be implemented without major land use change. Additionally, RAS located close to markets can significantly reduce CO_2 emissions associated with natural habitat destruction and fish transportation.

Apart from direct energy use and land use change, aquafeeds are also a major contributor to GHG emissions in aquaculture. In 2019, approximately 41 million tons of aquafeed were used in aquaculture globally (Ahmed and Turchini, 2021). Aquafeeds are the greatest source of GHG emissions in aquaculture due to the production, processing, storage, and transportation of raw materials from production areas to feed mills, and then the energy used in feed mills for processing and storage (Zhang et al., 2024). The compounded feed is then transported from mills to farms, resulting in further emissions (Robb et al., 2017). The GHG emissions related to aquafeeds are also coupled with feed conversion ratio (FCR), which can vary from 1.5 to 5 based on the farming intensity. Although the aquafeed utilized in RAS is the same as in other aquaculture practices, the technological, logistic, and biological advantages of operating in an indoor, controlled environment typically result in significantly increased feed efficiency and lower FCR (0.8–1.1) compared to other methods, leading to reduced feed-related GHG emissions (Yogev and Gross, 2019; Liu et al., 2016). Additionally, technologies such as biofloc and aquaponics in RAS can further reduce N_2O emissions (Hu et al., 2012). Aquaponics, in particular, can be practiced under greenhouse systems without affecting climatic factors, and if powered by renewable energy sources, can reduce total energy consumption and simultaneously reduce GHG emissions via direct carbon sequestration through photosynthesis by the cultured plants (Goddek et al., 2015). In contrast, in pond-based outdoor aquaculture farms

carbon is sequestered in pond sediments (Boyd et al., 2010). The use of fertilizers in extensive and semi-intensive aquaculture to grow natural food (e.g., plankton) can contribute to the release of GHG emissions (Robb et al., 2017). However, intensive fish production in RAS avoids the use of fertilizer-related GHG emissions since no fertilizers are used. RAS can help to reduce the carbon footprint of aquaculture production in several ways. According to Ebeling and Timmons (2012), RAS recirculates water continuously which reduces the amount of fresh water needed for aquaculture production. This can lead to significant energy savings and a lower carbon footprint as less energy is required to pump and treat water. Additionally, RAS systems are designed to filter and treat waste products allowing for the recovery of valuable nutrients and the reduction of environmental pollution (Turcios and Papenbrock, 2014; Rout et al., 2021). This can help to reduce the carbon footprint of aquaculture production by minimizing the release of pollutants into the environment. RAS systems enable more precise and controlled feed management which reduces feed waste and improves feed use efficiency without decreasing the actual nutritional requirements of the cultured organisms. Although RAS often operate at higher production intensities and therefore may require greater total feed inputs compared with earthen ponds, the reduction of unnecessary feed losses can lower feed usage in systems that would otherwise experience inefficient feeding. This improvement in feed use efficiency can consequently reduce the indirect carbon emissions associated with feed production and transportation (Ahmed and Turchini, 2021; Badiola et al., 2018). By adopting these systems, aquaculture producers can achieve more sustainable and environmentally responsible production practices. Table 1 highlights the positive and negative aspects of RAS in terms of carbon footprint when compared to traditional aquaculture systems. Overall, RAS systems have the potential to significantly reduce carbon footprint compared to traditional aquaculture systems (Zhang et al., 2024). However, the high capital investment and operating costs associated with RAS technology can make it challenging for some farmers to adopt this approach. Despite these challenges, the environmental benefits of RAS systems make them a promising solution for sustainable aquaculture.

To fully realize the potential of RAS systems to reduce carbon footprint, it is important to continue to develop and improve the technology. This includes reducing the capital investment and operating costs, as well as increasing the efficiency and effectiveness of RAS systems. Through research and development, innovation, and collaboration, the aquaculture industry can work towards making RAS technology more accessible and cost effective for farmers around the world. By doing so, we can promote sustainable aquaculture practices that reduce our environmental impact and help to build a more sustainable future.

To achieve this goal, we suggest several strategies that can support the continued development and improvement of RAS technology toward reducing its carbon footprint. These proposed strategies are based on the authors' synthesis of current knowledge. Unless supported by scientific evidence, they should be interpreted as recommendations rather than definitive requirements.

Research and development (R&D): We suggest strengthening R&D efforts to advance RAS technology and reduce its carbon footprint. Research institutions, universities, and private companies can invest in developing more efficient water treatment units, designing improved equipment, and optimizing system configurations to enhance energy efficiency. Such improvements may contribute to lower energy use, better water quality, and reduced carbon emissions.

Table 1. The positive and negative attributes of RAS in terms of carbon footprint compared to traditional aquaculture systems

Positive aspects
Water conservation RAS substantially reduce freshwater withdrawal by continuously treating and reusing water, leading to significantly lower water demand compared with flow-through or pond systems (Ebeling and Timmons, 2010, 2012; Timmons et al., 2006). Although reduced water use does not automatically translate into lower carbon emissions, improved water use efficiency can indirectly reduce energy required for large-volume water intake depending on the local hydrological context and system design.
Potential for lower carbon footprint per unit biomass Despite sometimes higher absolute energy use or GHG emissions due to aeration, pumping, and treatment processes, RAS can exhibit a lower carbon footprint per unit of biomass produced because of their higher productivity and much lower land requirements (Brown et al., 2025; de Melo Júnior et al., 2025; Martins et al., 2010). Even when emissions per unit area are higher, total emissions may be lower when land use impacts and production intensity are considered.
Improved environmental control and biosecurity RAS provide precise control over temperature, oxygen, and water quality, which enhances growth efficiency and reduces mortality (Badiola et al., 2018). Improved performance may reduce emissions intensity per kg of biomass produced.
Reduced discharge of nutrient-rich effluents Because water is recirculated, effluent volume is relatively small and nutrients can be better managed or removed, lowering the risk of eutrophication compared to open systems (Lal et al., 2024).
Negative aspects
High capital investment (economically important but not directly related to carbon footprint) RAS require advanced biofilters, pumps, oxygenation systems, and monitoring equipment. While this substantially increases investment costs, it does not directly influence carbon emissions (Badiola et al., 2018). It is nevertheless a critical limiting factor for adoption. particularly in low-resource settings.
Potentially high energy consumption Depending on regional water availability and system configuration, RAS may consume more energy than extensive pond systems, especially where ponds operate with no aeration or pumping (Badiola et al., 2018). When powered by nonrenewable energy sources, this can increase the carbon footprint. Renewable energy integration is therefore essential for minimizing GHG emissions.
High operating costs (not inherently linked to carbon footprint) Continuous operation of pumps, blowers, treatment units, and monitoring systems increases operational expenses. Although these costs affect economic feasibility, their relationship with carbon emissions depends entirely on the energy source used.
Dependence on stable energy supply RAS require uninterrupted operation of circulation and aeration systems. In regions with unstable electricity grids, backup generators (often diesel powered) may be necessary, potentially increasing emissions unless renewable alternatives are available.

Collaboration: We propose broader collaboration among universities, private companies, and government agencies as a strategy to accelerate progress in low-carbon RAS. Partnerships can support joint technology development, while governments may provide funding and regulatory support. Although such collaborations have strong potential benefits, their economic and environmental feasibility should be demonstrated through future research.

New technologies and promoting innovation: Improving the sustainability and carbon efficiency of RAS relies increasingly on practical, evidence-based technological innovations. Research has shown that upgrading energy intensive components such as low-head drum filters, optimized MBBR biofilters, and high efficiency or low-pressure oxygenation units can reduce pumping and aeration energy. Material innovations (e.g., recycled HDPE tanks, bio-based polymers, polypropylene piping) offer lower

embodied carbon than conventional FRP and PVC. Integrating renewable energy technologies, including rooftop photovoltaics solar thermal heating, and small-scale wind systems, has proven feasible in several commercial RAS installations. Additionally, policy tools such as grants, tax incentives, and innovation challenges have supported the adoption of low-carbon RAS solutions in regions like Norway and Denmark. Collectively, these innovations demonstrate viable pathways for reducing the carbon footprint of RAS (Aich et al., 2020; Badiola et al., 2012; Gupta et al., 2024; Manolache et al., 2025; Martins et al., 2010; Troell et al., 2004; Xiao et al., 2019).

Education and training: We suggest expanding education and training programs to ensure that future practitioners are equipped to design, build, and manage RAS facilities efficiently. Improving workforce capacity may support innovation, encourage best practices, and contribute to reducing the environmental impacts of aquaculture. Further studies are needed to evaluate the socioeconomic outcomes of such programs.

Regulation and policy: We recommend strengthening environmental regulations and policy frameworks that encourage sustainable aquaculture practices including the adoption of renewable energy, tax incentives for RAS investments, and requirements that limit environmental impacts. Such policies can help ensure that RAS facilities protect both marine habitats and freshwater ecosystems, particularly in regions where freshwater RAS is widely used, such as outdoor suspended tank systems in Brazil, thereby supporting long-term sustainability.

By pursuing the suggested strategies of research and development, collaboration, new technologies, innovation incentives, education, training, regulation, and policy stakeholders can contribute to a more sustainable and environmentally responsible aquaculture sector. While these strategies have strong conceptual potential to reduce the carbon footprint of aquatic food production, further studies are needed to fully validate their economic, environmental, and social feasibility.

Integrated multitrophic aquaculture (IMTA)

IMTA is a sustainable aquaculture approach in which species from different trophic levels are co-cultured within the same system so that the waste produced by fed species (e.g., finfish) becomes a resource for extractive species such as seaweeds and filter feeding shellfish. Unlike simple polyculture, IMTA explicitly relies on trophic complementarity to optimize nutrient recycling. By incorporating extractive species that naturally assimilate dissolved and particulate wastes, IMTA enhances nutrient efficiency, reduces reliance on external fertilizers, and can contribute to lowering the carbon footprint of aquaculture production (Chopin et al., 2012). According to Chopin et al. (2001), this nutrient recycling process can help to reduce environmental impacts associated with conventional aquaculture practices. Secondly, IMTA can reduce the discharge of waste products into the environment by utilizing the waste products of one species as a nutrient source for another. This can help to minimize the risk of environmental contamination and reduce the carbon footprint of production. Barrington et al. (2010) highlighted that IMTA can help to improve the sustainability of aquaculture by reducing the environmental impacts associated with waste disposal. Thirdly, IMTA can help to improve water quality by using multiple species in a single ecosystem. For example, seaweed can absorb excess nutrients in the water, which can help to prevent eutrophication and improve water clarity. This can lead to a healthier ecosystem and reduce the need for chemical treatments, which can contribute to the

carbon footprint of production. According to Chopin et al. (2001) and Khanjani et al. (2022), IMTA can help to restore ecosystem balance and improve the overall health of aquatic environments. Lastly, IMTA can reduce the energy required for aquaculture production. By reducing the need for chemical treatments and fertilizers less energy is required for their production, transport, and application. Additionally, by using seaweed to absorb excess nutrients, less energy is required for water treatment. This can help to reduce the carbon footprint of production and promote more sustainable production practices. Overall, IMTA is a sustainable aquaculture system that can help to reduce the carbon footprint of production and promote more efficient and environmentally responsible production practices (Nissar et al., 2023).

Table 2. Key positive and negative aspects of integrated multitrophic aquaculture (IMTA)

Positive aspects
Nutrient recycling
Reduced need for external inputs (feed, fertilizers)
Improved resource utilization efficiency
Potential reduction in carbon footprint
Enhanced water quality
Ecosystem diversification and biomitigation
Negative aspects
Complex multi-species management
Requirement for specialized knowledge (ecology, aquaculture, system design)
Need for specific environmental conditions
Limited scalability depending on site characteristics
Higher capital and infrastructure requirements
Potential resource competition between species

Table 2 presents the positive and negative aspects of IMTA regarding carbon footprint, compared to traditional aquaculture systems. When compared to traditional aquaculture systems, IMTA has the potential to reduce the carbon footprint, improve resource utilization, and reduce environmental impact. However, IMTA may be more complex to manage, may have limited scalability, and may require a higher capital investment. Despite these challenges, IMTA represents a promising approach to sustainable aquaculture and has the potential to reduce the environmental impact of the industry.

There are various strategies that can be employed to mitigate the negative aspects of IMTA regarding carbon footprint. One approach is to utilize renewable energy sources, such as solar or wind power to reduce energy consumption and promote a sustainable approach to aquaculture. Another potential strategy supported by several studies on IMTA performance is to optimize nutrient cycling through selective species choice, functional trophic complementarity, and appropriate stocking densities. Research has shown that aligning fed species (e.g., finfish) with extractive species (e.g., seaweeds, bivalves) can enhance nutrient capture efficiency and reduce reliance on external inputs such as fertilizers or high-protein feeds, thereby improving overall resource utilization (Chopin et al., 2012). Additionally, although IMTA has the capacity to mitigate nutrient wastes, it may still generate organic residues and emissions during harvesting, processing, and farm operations. Implementing best practices for waste reduction, effluent treatment, and emissions control such as improved solids capture, low-impact processing, and optimized handling protocols can further reduce environmental impacts and contribute to lowering the system's carbon footprint (Dalbem Barbosa et al., 2024; Filgueira et al., 2017, 2021).

Finally, we suggest adopting robust and science-based management practices, including continuous monitoring of water quality, disease risks, trophic balance, and nutrient flows, as these measures have been shown to improve system stability and enhance environmental performance

in multitrophic aquaculture settings (Troell et al., 2014; Barrington et al., 2010). Overall, applying sustainable operational practices and integrating validated technologies can support the reduction of carbon-related impacts in IMTA systems and contribute to broader climate mitigation objectives.

Freshwater IMTA faces notable limitations, mainly due to the restricted availability of suitable species at distinct trophic levels. Unlike marine systems, the freshwater sector lacks fast-growing inorganic extractive species with high nutrient uptake efficiency, and commonly used macrophytes may pose management or ecological risks. At the feed level, species such as tilapia, carp, and catfish often occupy overlapping omnivorous niches, reducing clear trophic complementarity, while freshwater deposit feeders (e.g., mussels, snails, oligochaetes) generally exhibit slower growth and greater sensitivity to environmental fluctuations which limits scalability. The overall efficacy of freshwater IMTA also varies across regions and production settings. Tropical systems tend to show faster growth and higher nutrient turnover but face greater risks of thermal stress, algal blooms, and disease outbreaks, whereas temperate systems are more stable but constrained by seasonal variation and lower biomass productivity. Similarly, open water environments offer lower operational costs but suffer from dilution effects and limited control over species interactions, while closed or land-based systems enable more effective nutrient coupling and higher environmental performance, albeit with greater infrastructure and management requirements. Overall, these constraints highlight the need for careful species selection, region specific design, and improved management practices to enhance the viability of freshwater IMTA.

Biofloc technology (BFT)

BFT is a sustainable and environmentally friendly solution for aquaculture that can help reduce the carbon footprint of production (Khanjani et al., 2025 a). BFT is a system that promotes the growth of microorganisms, such as bacteria and algae, which serve as a source of protein and other nutrients for the cultured species (Khanjani et al., 2025 b). This can reduce the need for external feed inputs, minimize waste, and reduce the demand for wild caught fish as a source of fishmeal. BFT technology has several advantages over traditional aquaculture practices. For instance, it reduces the need for external feed sources and chemical inputs, improving water quality, and reducing waste (Kuhn et al., 2016). In addition to improving water quality, BFT can reduce carbon footprint through several well-characterized mechanisms, including lower feed conversion ratios, reduced dependence on externally sourced protein ingredients, and decreased water exchange requirements compared with conventional earthen ponds, flow-through systems, or outdoor cages. In shrimp farming for example, BFT allows in situ microbial protein production and has been shown to reduce the need for external feed inputs by up to 30%, leading to measurable reductions in carbon emissions associated with feed manufacture and transport (Samocha, 2019; Dinda et al., 2019). Similarly, in tilapia farming BFT has achieved reductions in carbon footprint of up to 70% relative to traditional pond-based culture, largely due to lower chemical inputs, enhanced nutrient retention, and diminished pumping and water replacement requirements (Kuhn et al., 2016). Evidence from catfish culture also indicates improvements in nutrient recycling and decreased discharge volumes, highlighting the potential of BFT to outperform conventional open water or semi-intensive systems in terms of carbon efficiency. Overall, these comparisons demonstrate that BFT can substantially reduce GHG emissions when benchmarked against common freshwater and brackishwater production systems. Firstly, BFT

technology uses microorganisms to convert waste into protein-rich feed that can be used to feed the fish and shellfish (Khanjani et al., 2024; Mahmoudi et al., 2025). This reduces the need for external feed sources, improving production efficiency, and reducing the carbon footprint of aquaculture. By using microorganisms BFT technology can reduce the need for fishmeal and other external feed sources, which require significant amounts of resources and energy to produce (Mandal and Das, 2018). Secondly, BFT technology helps to reduce waste by using microorganisms to convert waste into protein-rich feed (Khanjani, 2025). In traditional aquaculture practices, excess feed and waste products can accumulate in the water and sediment leading to environmental degradation and carbon emissions. BFT technology improves water quality by converting waste products into a beneficial food source for the farmed species, reducing the amount of waste generated and promoting sustainable practices (Das and Mandal, 2021; Khanjani and Sharifinia, 2024; Khanjani and Alizadeh, 2024). Lastly, BFT technology can promote sustainable practices by reducing the environmental impact of aquaculture (Pimentel et al., 2026). It reduces the need for external inputs, such as feed and chemicals, and improves water quality, leading to healthier fish and better production efficiency. By promoting sustainable operational practices, BFT can contribute to reducing the carbon footprint of aquaculture; however, its performance varies depending on energy sources, system design, and management. Compared to conventional systems such as earthen ponds, flow-through raceways, and open cages, BFT shows both strengths and limitations in terms of carbon efficiency (Table 3).

Overall, while BFT systems have the potential to reduce the carbon footprint of aquaculture compared to traditional systems, there are also potential challenges that need to be addressed to maximize their environmental benefits. In order to optimize the environmental benefits of BFT systems and minimize their carbon footprint, it is recommended to implement several strategies. Based on the evidence presented in Table 3 and the broader BFT literature, we suggest several strategies that can enhance the carbon efficiency and environmental performance of BFT systems. The integration of renewable energy sources such as solar or wind power has been shown to substantially reduce energy-related emissions in aeration intensive systems (Emerencio et al., 2025). Similarly, optimizing nutrient management through appropriate C:N ratios, careful feed formulation, and routine monitoring of microbial community dynamics can mitigate GHG emissions, particularly CO_2, CH_4, and N_2O, which may arise during organic matter decomposition (Dinda et al., 2019).

Table 3. Key positive and negative aspects of biofloc technology (BFT) in relation to carbon footprint

Positive aspects
Reduced external feed inputs
Improved nutrient recycling
Lower water-exchange requirements
Reduced effluent discharge
Negative aspects
High energy demand (aeration, mixing)
Increased capital requirements
Potential GHG* generation
Management complexity

*CO_2, CH_4, N_2O.

We also recommend implementing established best practices for waste reduction and emissions control including solids capture, improved sludge handling, and low emission transport and processing methods, all of which have been associated with measurable decreases in operational carbon footprint in intensive aquaculture systems (Emerciano et al., 2025; Pimentel et al., 2026). Regular water quality monitoring remains essential, as stable microbial

function is directly linked to nutrient retention and reduced environmental impacts. Finally, adopting sustainable management practices such as monitoring disease risks, maintaining appropriate stocking densities, and ensuring balanced nutrient cycling can further improve resource use efficiency and reduce the environmental burden of BFT operations. Collectively, these author recommended strategies, grounded in prior empirical findings can increase the environmental benefits of BFT while contributing to the reduction of system-level carbon emissions.

Aquaponics

Aquaponics combines aquaculture with hydroponics, where the waste produced by aquatic organisms is used as a nutrient source for plants (Stoyanova et al., 2024). This system can reduce the carbon footprint of production by minimizing waste and reducing the need for external inputs such as fertilizers. Aquaponics can be used for a variety of species, including tilapia, catfish, and trout, as well as for growing vegetables and herbs (Goddek et al., 2015; Pinho et al., 2022). Aquaponics offers several ways to reduce carbon footprint. With its closed loop system, aquaponics uses significantly less energy compared to traditional agriculture practices, as there is no need for tilling, plowing, or extensive irrigation (Ibrahim et al., 2023).

This means that less energy is needed to pump and distribute water, reducing energy consumption and GHG emissions (Fang et al., 2017; Ghamkhar et al., 2020). In contrast to traditional aquaculture that heavily relies on chemical fertilizers, aquaponics uses fish waste to provide nutrients to plants, eliminating the need for chemical fertilizers that contribute to GHG emissions (Rakocy, 2012; Enduta et al., 2011). Aquaponics also reduces transportation emissions by enabling crops to be grown in urban areas, closer to the consumers, which significantly reduces transportation distances and emissions (Greenfeld et al., 2019; Joyce et al., 2019). Finally, aquaponics conserves water by recirculating water, reducing the need for pumping and distribution, and the associated carbon emissions from energy production (Ondruška et al., 2022; Goddek et al., 2019 a). Overall, aquaponics is an environmentally sustainable farming system that reduces carbon footprint through energy efficiency, water conservation, elimination of chemical fertilizers, and reduced transportation emissions. Given the growing concern over climate change and the need to reduce emissions, aquaponic systems may offer a potential approach for lowering the environmental impacts of food production. Previous studies indicate that aquaponics can reduce dependence on externally manufactured fertilizers because nutrients from fish effluent are reused within the system (Somerville et al., 2014). This nutrient recycling, combined with lower water requirements compared to conventional aquaculture or hydroponics, can contribute to reduced carbon emissions associated with input production, transportation, and water treatment (Goddek et al., 2015). Some research also suggests that reliance on external feed inputs may be partially reduced through improved nutrient retention, which further contributes to potential carbon savings (Love et al., 2015).

However, these benefits are not guaranteed and depend on system design, energy sources, and local conditions. Heating, water circulation, and lighting can significantly increase energy consumption, especially when nonrenewable electricity is used (Goddek et al., 2019 a, b). Moreover, aquaponics often operates at smaller scales than conventional aquaculture, and this may reduce its overall carbon efficiency if system optimization is lacking. Therefore, the environmental advantages of aquaponics should be understood as context-dependent potentials rather than universal outcomes. Table 4 summarizes the main positive and negative attributes of aquaponic systems in relation to carbon footprint.

Table 4. Key positive and negative attributes of aquaponic systems regarding carbon footprint

Positive aspects
Reduced external nutrient inputs
Improved resource utilization
Lower water use
Integrated plant fish nutrient recycling
Negative aspects
High energy demand (pumping, heating, lighting)
Limited production scale
High initial capital requirements
System management complexity

To enhance the environmental performance of aquaponic systems and potentially reduce their carbon footprint, several strategies can be implemented that are already supported by previous empirical and applied research. Studies have shown that integrating renewable energy sources such as solar or wind power can lessen dependence on nonrenewable electricity and thereby contribute to lower system-level emissions (Zakariazadeh et al., 2024). Likewise, research on system optimization demonstrates that improving the design and operation of aquaponic units can support more efficient use of water and energy, which has been associated with reduced environmental impacts across different production settings (Zakariazadeh et al., 2024).

Evidence also indicates that applying waste reduction measures and adopting low-emission processing and transport practices can help limit the indirect environmental burdens of aquaponic operations. Regular monitoring of water quality has been repeatedly emphasized in the literature as essential for sustaining microbial activity, maintaining system stability, and preventing management-related inefficiencies that may increase emissions. Furthermore, studies focusing on sustainable management approaches such as disease risk monitoring, nutrient cycling control, and improved operational planning suggest that these practices can support more effective resource use and mitigate environmental impacts (Ngwenya et al., 2025; Emerenciano et al., 2025).

Adoption of sustainable and organically certified feed ingredients has also been proposed as a feasible pathway to reduce upstream environmental pressures associated with feed production. Collectively, these strategies draw upon previously tested approaches reported in the literature, and their effective implementation may enhance the environmental advantages of aquaponic systems while contributing to lower carbon emissions within the broader aquaculture sector (Lobanov et al., 2025).

Challenges and future prospects

Innovative aquaculture systems have the potential to support lower carbon footprints; however, several challenges must be addressed to realize these benefits. One key issue is the substantial initial investment required for installing advanced technologies, which can limit adoption, especially in developing regions. Technical complexity also remains a barrier, as many of these systems require specialized knowledge and operational skills that are not universally available.

Another challenge concerns the indirect emissions associated with energy use and infrastructure. In RAS, most GHG emissions reported in life cycle assessments originate from indirect sources, particularly electricity consumption for pumping, aeration, and temperature control, as well as the materials used for constructing tanks, pipes, and filtration units (Martins et al., 2010; Midilli et al., 2012; Yogev and Gross, 2019). Direct emissions from the culture units themselves are generally considered minor within carbon footprint accounting.

While innovative system components such as biofilters and bioreactors are essential for water recirculation and nitrogen transformation, several studies highlight that the biofilter can also be a major location

where GHG production occurs due to the accumulation and microbial degradation of organic sediments (Bollon et al., 2016; Fernandes et al., 2017; Ruiz et al., 2020).

Therefore, simply installing a biofilter does not reduce emissions by itself; rather, reductions depend on effective management practices, including solids removal, flow optimization, and the prevention of anaerobic zones. Furthermore, although RAS may exhibit relatively high absolute emissions, their high productivity can still result in a comparatively low-carbon footprint per unit of biomass produced, a point emphasized in the literature and relevant for interpreting their environmental performance.

Despite these challenges, innovative systems such as aquaponics demonstrate promising opportunities for improving resource efficiency and reducing waste by integrating hydroponic plant production with aquatic nutrient recycling. Continued research and development are needed to refine these technologies, reduce energy demand, and expand practical guidance for operators. Efforts aimed at knowledge transfer, capacity building, and technology adaptation can further facilitate broader adoption. By addressing these constraints and grounding system design in evidence-based practices, innovative aquaculture systems can make meaningful contributions toward lowering the sector's carbon footprint and advancing more sustainable production models.

Conclusion

Overall, these innovative aquaculture systems have the potential to revolutionize the industry by promoting sustainability, reducing carbon emissions, and contributing to a more resilient and equitable food system. However, their successful implementation requires a holistic approach that considers the economic, social, and environmental dimensions of sustainability. The aquaculture industry can play a critical role in addressing global food security and sustainability challenges, and these innovative systems can help to pave the way toward a more sustainable and low-carbon future.

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Received: 6 XI 2025
Accepted: 3 II 2026