

Integrated Multi-Trophic Aquaculture in Freshwater Systems in the Context of the Circular Economy – a Review

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Abstract

Aquaculture is among the fastest-growing industries worldwide, playing a key role in feeding a continuously expanding global population. This accelerated development calls for the adoption of innovative technologies, efficient culture systems, and sustainable production practices. In this context, recirculating aquaculture systems (RAS) are considered a strategic solution for meeting the increasing demand for aquatic products, thanks to their capacity to optimize resource use and reduce environmental pressure. Additionally, the integration of new and adaptable species into Integrated Multi-Trophic Aquaculture (IMTA) or aquaponic systems, especially in freshwater environments, significantly enhances the efficiency and sustainability of modern aquaculture. Integrating IMTA into RAS enables efficient water use, more rigorous biosecurity control, and a significant reduction in nutrient emissions. Moreover, incorporating hydroponic components enhances the benefits of these systems by allowing the cultivation of edible plants that utilize residual nutrients and contribute to strengthening the circular nature of the system. Through resource valorization, waste reduction, and production diversification, IMTA emerges as a key model for modern, sustainable, and responsible aquaculture, with a positive impact on ecosystem health and global food security. This review synthesizes the most recent research on IMTA, highlighting its potential in the transition towards sustainable aquaculture, in full alignment with the principles of the circular economy. IMTA involves the co-cultivation of species from different trophic levels within a system that transforms organic and inorganic waste into valuable resources for other cultured organisms. This model optimizes nutrient use, reduces environmental impact, and diversifies production, while also offering additional economic opportunities.

Keywords: circular economy, Integrated Multi-Trophic Aquaculture, recirculating aquaculture system.

1. Introduction

Aquaculture currently represents one of the most dynamic and promising sectors of global food production, playing a crucial role in ensuring food supply for a continuously growing world population [1, 2]. According to FAO (2024), global fisheries and aquaculture production in 2022 reached 223.2 million tonnes, comprising 185.4 million tonnes of aquatic animals and 37.8 million tonnes of algae. This record level represents a 4.4 % increase relative to 2020, and is

accompanied by FAO's narrative of a “Blue Transformation” pointing toward a gradual shift in the industry toward more sustainable and controlled forms of aquatic production — though the data alone do not fully establish the pace or dominance of that transition [3].

A particularly relevant development is that, for the first time, the quantity of aquatic animals produced through aquaculture (94.4 million tonnes) exceeded that from capture fisheries, meaning that aquaculture accounted for 51% of the total global supply of aquatic animal products available for consumption. This historic shift in the balance between the two sources highlights the transition toward a more controllable and predictable industry, with reduced impact on natural ecosystems [3].

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Freshwater aquaculture accounted for 59.1 million tonnes in 2022, representing 62.6% of the global aquaculture production of aquatic animals [4].

Nevertheless, the sector's positive development is accompanied by ecological and sustainability challenges that cannot be ignored. Biological productivity and the balance of aquatic ecosystems, especially marine ones, are becoming increasingly vulnerable to pressures generated by human activities. Climate change, chemical and organic water pollution, as well as the overexploitation of fisheries resources, cumulatively contribute to the degradation of aquatic habitats, the loss of biodiversity, and the disruption of natural processes of ecological regulation [5-7]. These impacts threaten not only the capacity of ecosystems to sustain aquatic resource production but also the socio-economic resilience of the communities that rely on these activities.

These challenges highlight the pressing need to rethink aquatic production models within a framework that combines economic efficiency with environmental protection. Despite technological progress, conventional aquaculture continues to raise concerns about its long-term sustainability and its impact on aquatic ecosystems. Among the most pressing issues are the intensive exploitation of natural resources, particularly freshwater and land [8-13].

In this context, the transition to sustainable production models becomes imperative, where modern aquaculture is not only an economically efficient sector but also a responsible actor in managing natural resources and protecting the global ecological capital. The sustainable development of aquaculture is not founded on a single technology but on a set of complementary solutions adapted to local conditions [14]. A relevant example is Hungary, where the evolution of integrated pond systems has relied on the establishment of multifunctional fishponds that enable efficient use of natural resources [15]. The diversification of aquatic species, including fish, has enhanced nutrient utilization and reduced the economic risks associated with monoculture.

Given these challenges, it is clear that aquaculture must embrace innovative, sustainable technologies to secure growth without endangering ecological stability. Promising solutions include Recirculating Aquaculture Systems (RAS), which provide full environmental control and reduce water demand, and Integrated Multi-Trophic

Aquaculture (IMTA), which transforms the waste of higher trophic species into valuable inputs for lower trophic organisms. These systems not only enhance resource efficiency but also reduce waste, maintain water quality, and expand the range of products obtained, representing viable strategies for the sustainable development of aquaculture [16-19].

Beyond ecological benefits, IMTA systems present significant economic potential through the valorization of by-products, the diversification of production, and greater consumer acceptance, which can lead to higher profitability and reduced costs associated with negative externalities [20].

Recirculating Aquaculture Systems (RAS) are modern land-based technological solutions that function as closed-loop systems and employ advanced biofiltration to ensure continuous water purification, remove toxic compounds, and maintain optimal parameters for fish growth [21-27].

RAS are primarily applied in the cultivation of economically valuable species such as salmon, trout, tuna, and shrimp, benefiting from recent advancements in digital technologies that enable real-time monitoring, feeding optimization, and enhanced management of aquatic animal welfare [28, 29]. Moreover, RAS provides viable solutions for water-scarce regions and contributes to nutrient recycling while mitigating environmental impacts [30-35]. In this context, several countries support the development of RAS through dedicated policies [36, 37]. Overall, the integration of RAS into modern aquaculture strategies can facilitate the transition toward sustainable, efficient, and environmentally sound production systems [38]. Although RAS provides an advanced technological solution for sustainable and high-yield aquaculture, its efficiency can be further increased by integrating the principles of Integrated Multi-Trophic Aquaculture (IMTA). The application of IMTA within RAS enables the optimal utilization of available resources and reduces environmental impacts by co-cultivating species occupying complementary trophic niches. IMTA entails the integrated culture of species at different trophic levels, which utilize residual nutrients (uneaten feed, metabolic waste) generated by primary species, thereby promoting resource recycling in line with circular economy principles [39, 40].

Proper species selection secures ecological balance and achieves higher yields than

monoculture, while also ensuring economic value and providing biofiltration functions [41-43]. Consequently, the integration of RAS and IMTA not only enhances production efficiency but also reinforces the ecological and economic dimensions of aquatic systems. From this perspective, IMTA stands out as a sustainable strategy, compatible with diverse climatic zones—both temperate and tropical—and perfectly aligned with the principles of the circular economy.

By integrating biological resources, this model contributes to food security and strengthens the

capacity of aquaculture systems to address the challenges posed by climate change and the pressures on global food supply chains [17, 44]. The idea of simultaneously cultivating multiple aquatic species at different trophic levels has distant origins. The earliest references appear in the Chinese agricultural treatise *Nong Zheng Quan Shu* (1639), which describes traditional systems of integrated culture involving fish, plants, and animals, as well as the use of natural fertilizers to support aquaculture productivity [43].

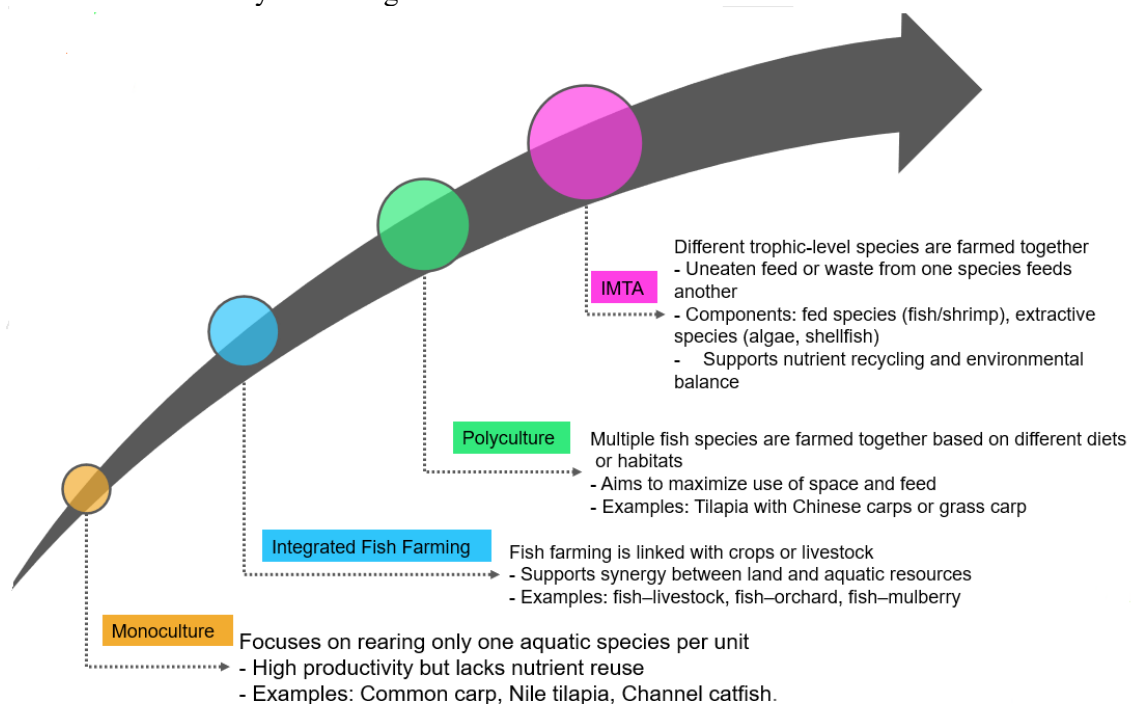


Figure 1. The Development of IMTA Systems

An important step in modernizing these concepts took place in the 1970s, when researcher John Ryther initiated an experimental project on the reuse of nutrients resulting from fish farming activities by introducing algae and mollusks into marine systems, thereby reviving interest in the ecological valorization of waste [45].

Subsequently, in the early decades of the 21st century, the approach was expanded and refined through various forms of integrated culture, such as polyculture and ecological systems, which combine diverse species adapted to local conditions and fulfilling complementary roles in the trophic chain [43].

The term Integrated Multi-Trophic Aquaculture (IMTA) was coined in 2004 by Thierry Chopin

and Jack Taylor, with their proposal emphasizing the recycling of residual nutrients through species

diversification within the system, so that each biological category contributes to the overall stability and efficiency of the cultivated aquatic ecosystem [43]. The adoption of such sustainable solutions is crucial not only for achieving food security objectives but also for reinforcing the ecological and economic resilience of aquatic systems. In this framework, modern aquaculture is no longer perceived merely as a source of food but as a central strategic element in the transition toward a circular, adaptable, and environmentally responsible economy. In this regard, the future success of aquaculture depends on optimizing

system performance, integrating emerging technologies, and reducing costs, in order to ensure efficient, sustainable, and accessible production amid increasingly scarce resources [46].

2. Enhancing the Sustainability of Aquaculture through Integrated Multi-Trophic Aquaculture (IMTA) Systems

In the context of growing pressures on aquatic ecosystems and the need to transition toward a circular economy, Integrated Multi-Trophic Aquaculture (IMTA) systems provide a sustainable, efficient, and adaptable alternative for aquaculture production. By integrating species from different trophic levels (fish, plants, crustaceans, etc.), IMTA contributes to nutrient recycling, reduces pollution, and increases the economic value of aquaculture systems. This approach promotes not only economic performance but also the ecological and social sustainability of modern aquaculture [47].

The following section presents the main directions through which IMTA contributes to enhancing aquaculture sustainability:

Reducing Environmental Impact

One of the most important benefits of Integrated Multi-Trophic Aquaculture (IMTA) systems is their capacity to reduce the pressure on aquatic ecosystems by utilizing residual nutrients and recycling resources within the same production structures. Through the co-cultivation of species from different trophic levels, the organic waste generated by higher organisms, such as fish, becomes a valuable resource for mollusks and algae, contributing to the maintenance of water quality and the reduction of pollution. This approach represents a key tool for the sustainable management of aquaculture, particularly in the context of climate change and the depletion of natural resources [17].

In freshwater systems, the integration of IMTA into fishponds has stimulated plankton productivity and reduced dependence on external inputs. Organic fertilization and microhabitat management have increased the availability of natural trophic resources while simultaneously limiting excessive nutrient accumulation and the risk of eutrophication [48]. IMTA systems have also proven effective in managing waste generated by intensive aquaculture, contributing to the

improvement of ecological conditions in culture ponds. However, to support their large-scale adoption, further research is required on the economic and social implications of such systems [47]. Other studies, under mesocosm conditions, have demonstrated the role of the freshwater mussel *Sinanodonta woodiana* in the bioremediation of wastewater from trout farms. At an optimal density of 7.5 kg/m³, these bivalves reduced the general bacterial concentration by up to 72% and the *Aeromonas hydrophila* load by 95–98%, highlighting their potential as biotechnological tools in combating antimicrobial resistance in continental aquaculture systems [49]. In the same direction, the efficiency of aquatic plants *Ipomoea aquatica* and *Brassica juncea* was tested in aquaponic systems with African catfish (*Clarias gariepinus*), demonstrating reductions of over 80% in major inorganic pollutants (N-NH₄⁺, NO₂⁻, NO₃⁻, PO₄³⁻). The aquatic vegetation significantly contributed to nutrient recycling and the preservation of water quality [50].

To reduce the ecological impact of aquaculture, the integration of waste stabilization ponds (WSP) into IMTA structures has shown high potential in decreasing nutrient concentrations and increasing dissolved oxygen levels in recirculating systems. The use of *Lemna* sp., together with water treatment in WSP, improved water quality, suggesting the efficiency of this method in aquaculture effluent purification and in reducing the impact on aquatic environments [51].

Increased Efficiency in Resource Utilization

IMTA systems enable efficient and enhanced valorization of available aquaculture resources by integrating species from different trophic levels that utilize nutrients in a complementary manner. This approach enhances production efficiency and minimizes losses by transforming the biological waste generated by higher-trophic species into valuable inputs for lower-trophic organisms. Through this internal recycling mechanism, IMTA optimizes the conversion of resources into biomass, supporting system productivity without compromising ecosystem sustainability [17].

An applied example is the implementation of IMTA principles in freshwater fishponds, where organic fertilization and careful microhabitat management resulted in a significant increase in plankton populations, a valuable natural trophic resource for fish. This strategy reduces dependence on commercial feeds and improves

the cost-efficiency of production. In an experimental setup using a mixture of 60% fermented manure and 40% sheep manure, combined with appropriate pond protection measures, a significantly higher natural biomass was achieved, demonstrating complete resource utilization and superior yield per unit area [48]. Models of polyculture and integrated culture applied in the farming of largemouth bass (*Micropterus salmoides*), in association with planktivorous and filter-feeding species such as Prussian carp (*Carassius gibelio*), silver carp (*Hypophthalmichthys molitrix*), and the freshwater pearl mussel (*Hyriopsis cumingii*), contributed to improved water quality by reducing ammonia concentrations and increasing dissolved oxygen levels. Although growth performance did not differ significantly, the use of such models demonstrates tangible ecological potential for the sustainable development of freshwater aquaculture [52].

Another relevant example is the evaluation of a recirculating aquaponic system in which freshwater giant prawns (*Macrobrachium rosenbergii*) were co-cultivated with lettuce (*Lactuca sativa*). The results indicated that supplementation with organic and mineral nutrients increased yields without negatively affecting water quality parameters. This study highlights the importance of a balanced nutritional formulation in optimizing resource utilization in co-culture systems [53].

To support this transition toward circular models, the future of intensive aquaculture—including IMTA systems—is closely linked to the adoption of technologies such as RAS (Recirculating Aquaculture Systems), bio-RAS, BFT (Biofloc Technology), IPRS (In-Pond Raceway Systems), and partitioned aquaculture systems (PAS/SPs). These approaches substantially reduce water, energy, and feed consumption while minimizing waste generation [54]. At the same time, they strengthen resource-use efficiency and foster the integration of modern aquaculture within the circular economy paradigm, in which nutrient flows are fully valorized and production costs can be considerably reduced.

Complementary to these technological solutions, the optimization of IMTA systems is also supported by the development of mathematical models capable of accurately describing the complex interactions between cultivated species, with the aim of determining the most effective

combinations and the optimal yields for each trophic level. The simulation of different co-culture scenarios enables the maximization of natural resource utilization and more effective control over the production cycle. Such tools contribute to the sustainable expansion of aquaculture, increase sectoral revenues, and reduce environmental impact, particularly through by-product valorization and the ecological interactions among organisms [55].

Added Value through By-products

Another key benefit of IMTA systems consists in their capacity to transform biological waste—such as excretions and uneaten feeds—into valuable resources for other aquatic organisms. The integration of lower trophic-level species allows for the expansion of the range of products obtained, the complete valorization of available nutrients, and the generation of an economically valuable secondary biomass. In this way, the system becomes more efficient and profitable, supporting the principles of the circular economy [17].

Enhancing Social Acceptability

The social acceptance of sustainable aquaculture, including Integrated Multi-Trophic Aquaculture (IMTA) systems, is strongly influenced by the public's level of awareness, trust, and overall perception of these practices. Among European populations, confusion and skepticism toward sustainability statements persist, while concepts such as RAS and IMTA remain little known. Addressing these ambiguous perceptions requires the development of transparent communication strategies, supported by scientific certification and direct consumer involvement through interactive platforms [57].

Although IMTA is generally associated with sustainability, the lack of adequate information limits its potential for large-scale expansion. A clearer understanding of the ecological and economic benefits offered by integrated aquaculture systems can be fostered through educational campaigns and outreach efforts tailored to specific socio-cultural contexts. Strengthening public acceptance requires not only effective communication but also the active participation of communities in the transition toward sustainable aquaculture, based on trust and genuine social support [58].

Contribution to the Sustainable Development Goals (SDGs)

Integrated Multi-Trophic Aquaculture (IMTA) systems constitute an innovative solution in aquaculture, capable of supporting the transition toward sustainable, efficient, and responsible food production, thereby directly contributing to the achievement of the Sustainable Development Goals (SDGs).

By enhancing the capacity of aquaculture systems to provide food sustainably, amid shrinking resources and worsening nutritional imbalances, IMTA becomes a key instrument for reinforcing global food security [17]. At the same time, this production-oriented approach brings significant improvements in resource utilization efficiency and in the quality of aquatic products and co-products, contributing to objectives such as SDG 14 (Life Below Water) by promoting sustainable aquaculture practices and reducing the impact on aquatic ecosystems. The alignment of IMTA systems with ESG (Environmental, Social and Governance) principles and with the new European legislative directions on the restoration of degraded habitats supports both ecological and economic sustainability [59]. Moreover, the link between IMTA and the circular economy is reinforced by the development of simple yet effective indicators that can be employed to monitor the performance of aquaculture systems in the absence of more complex tools such as Life Cycle Assessment (LCA) [60]. Thus, IMTA is emerging as a strategic option within food and climate policies, fostering a genuine transition toward production models that operate within planetary boundaries. A concrete example of the alignment of IMTA principles with SDGs is provided by an innovative model implemented on Irish peatlands, where an integrated multi-trophic system powered by wind energy employs microalgae for natural water treatment, without the use of pesticides, antibiotics, or effluent discharge. This ecological approach directly contributes to the achievement of several SDGs, including SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water). The results highlight the potential of IMTA systems to support the transition toward a circular, adaptive, and resilient economy [61].

3. Diversification of aquaculture production through Integrated Multi-Trophic Aquaculture (IMTA): co-cultivation of species at different trophic levels

The diversification of aquaculture production can be efficiently achieved through the implementation of Integrated Multi-Trophic Aquaculture systems, which enable the co-cultivation of species belonging to different trophic levels by valorizing the natural ecological interactions among them.

In certain cases, diversification can also be achieved at the same trophic level, in the form of polyculture, in which species selection relies on behavioral compatibility, particularly with respect to feeding regimes and spatial distribution (territoriality) of fish.

Polyculture: Co-cultivation of multiple fish species

Production diversification in aquaculture can be achieved through the co-cultivation of species from different trophic levels within Integrated Multi-Trophic Aquaculture (IMTA) systems, valorizing the natural ecological interactions among them.

Most studies on fish polyculture have been carried out in extensive and semi-intensive pond systems, since the efficient use of nutrients and the maximization of yields represent challenges common to all aquaculture systems. In Chinese aquaculture, after a period of intensive monoculture with high-value species such as common carp (*Cyprinus carpio*), crucian carp (*Carassius carassius*), grass carp (*Ctenopharyngodon idella*), and Nile tilapia (*Oreochromis niloticus*), there has been a partial reversion to traditional polyculture models through the introduction of plankton-feeding species such as silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*H. nobilis*).

This strategy aimed to reduce excessive phytoplankton accumulation, a phenomenon fostered by the organic matter derived from feces and uneaten feed [62].

A contemporary model, known as the “80:20 system” and promoted by the American Soybean Association, recommends that 80% of production be represented by high-value species, while the remaining 20% consist of filter-feeding species, such as silver carp (*H. molitrix*), to maintain biological balance in pond systems.

The implementation of this model, coupled with the use of balanced extruded feeds and ponds equipped with water recirculation and aeration,

has resulted in higher yields, accelerated growth rates, and a reduced ecological impact [63, 64].

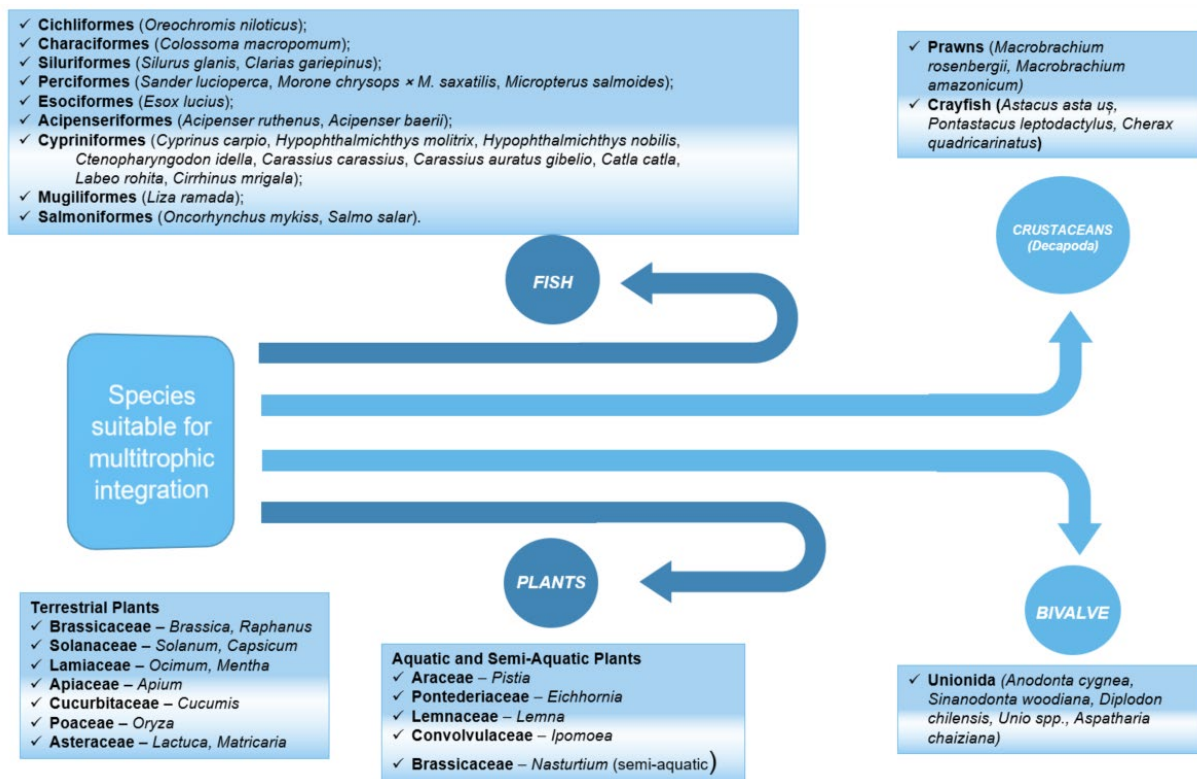


Figure 2. Representative species commonly used in Integrated Multi-Trophic Aquaculture (IMTA) systems

In this context, the transition toward more sustainable aquaculture practices, including the adoption of environmentally friendly models, requires the development of rigorous guidelines on nutrition, disease control, and efficient resource utilization, with the aim of maintaining environmental quality even under intensive production conditions [65].

A complementary approach was evaluated in Egyptian farms, where the co-cultivation of African catfish (*Clarias gariepinus*) at a ratio of 25% with Nile tilapia (*Oreochromis niloticus*) led to improved production performance without compromising water quality. This strategy highlights the potential of polyculture systems in optimizing yields and promoting sustainability in freshwater aquaculture [66]. Moreover, polyculture of tilapia with African catfish, applied at medium and high stocking densities, resulted in improved growth performance and higher yields compared to monoculture, indicating clear economic benefits, particularly at medium density,

which was considered optimal from a cost-efficiency perspective [67].

The integration of pond–cage systems represents an efficient solution for increasing productivity, enabling enhanced utilization of feed and grow-out space, particularly for species such as Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*), and common carp (*Cyprinus carpio*) [68]. In other combinations, the polyculture of European catfish (*Silurus glanis*) with sturgeons (Acipenseridae) resulted in significant weight gains without affecting survival, indicating the need to optimize feed rations for both species in pond-based systems [69]. The valorization of natural resources, especially zooplankton, was influenced by the introduction of bighead carp (*H. nobilis*), a planktivorous species that competed trophically with *Polyodon spathula* in unfed ponds, leading to a rapid decrease in zooplankton abundance and an adaptation in feeding behavior [70].

Among the high-yield combinations, the association of Nile tilapia (*Oreochromis niloticus*)

with common carp (*Cyprinus carpio*) and silver carp (*H. molitrix*) stands out, owing to the complementarity of feeding behavior, which enables efficient utilization of available resources. Predatory species such as pikeperch (*Sander lucioperca*) and European catfish (*Silurus glanis*) have also been employed for the biological control of diseased or invasive fish [71].

In Bangladesh, the polyculture of tilapia with *Cirrhinus mrigala* and *Labeo rohita* was optimized through the extension of the nursery phase and the application of inorganic fertilizers, particularly in eutrophic pond systems [72].

The association of pike (*Esox lucius*) with sturgeon in tank-based polyculture systems has demonstrated enhanced feed conversion efficiency and reduced maintenance requirements, outcomes attributed to the complementary trophic behaviors of the two species. By consuming uneaten feed, the pike reduced the need for manual interventions during the sturgeons' growth period [73].

Other promising combinations in recirculating aquaculture systems (RAS) include the co-culture of pikeperch (*Sander lucioperca*) fingerlings with sterlet (*Acipenser ruthenus*) or European catfish (*Silurus glanis*). These species have demonstrated effective functional complementarity, contributing to increased total biomass by valorizing uneaten feed, without negatively affecting the growth dynamics of the sturgeons [74-76].

In the case of the co-culture of sterlet (*Acipenser ruthenus*) with common carp (*Cyprinus carpio*), the growth dynamics of sterlets were not significantly affected; however, the inclusion of 30% carp resulted in the most favorable bioproductive performance, indicating the superior efficiency of this association [77]. In a similar model, European catfish (*Silurus glanis*) proved to be an effective auxiliary species in intensive sturgeon farming, valorizing uneaten feed from sterlets and contributing to the accumulation of additional biomass within the system [78, 79].

Another successful example is the polyculture of largemouth bass (*Micropterus salmoides*) with gibel carp (*Carassius gibelio*) and silver carp (*H. molitrix*) in a controlled semi-intensive system. This combination reduced ammonium concentrations and increased dissolved oxygen levels, without negatively affecting the growth performance of largemouth bass or the efficiency of nitrogen and phosphorus utilization. These results highlight the potential of polyculture as an optimized model for commercial largemouth bass farming, contributing to improved water quality and enhanced ecological stability [52].

Aquaponics: Integrated Co-culture of Fish and Plants

Aquaponic systems integrate recirculating aquaculture systems (RAS) with hydroponic technologies within a closed ecological cycle, in which fish, plants, and microbial communities interact synergistically to sustain water quality and ensure efficient nutrient recycling [80, 81, 85]. Aquaponics combines the water-reuse capacity characteristic of RAS—recovering over 90% of the total volume through biological and mechanical filtration—with the soilless plant production inherent to hydroponics, thereby valorizing aquatic waste streams as nutrient sources for crops [85-87].

The primary objective of aquaponics is to transform the organic waste generated by fish farming into plant-available nutrients, thus simultaneously generating two marketable products. Through the activity of nitrifying bacteria, ammonia and ammonium excreted by fish are biologically converted into nitrites and subsequently into nitrates—forms of nitrogen readily assimilated by plants [82, 83]. The plants absorb these nutrients from the water, thereby contributing to the purification of the aquatic environment, while the purified water is recirculated back into the fish tanks, closing a sustainable and efficient cycle [82, 83].

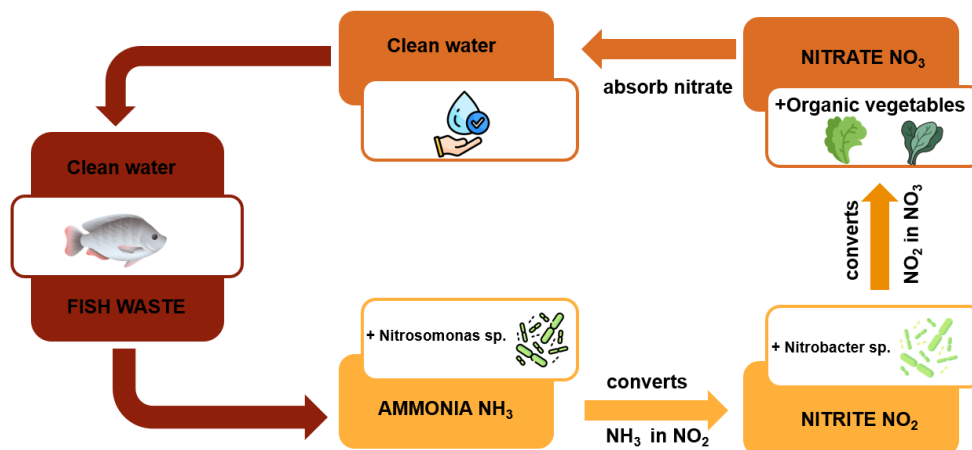


Figure 3. Nutrient dynamics in aquaponic systems. Fish waste releases ammonia (NH_3), which is oxidized by *Nitrosomonas* spp. into nitrite (NO_2^-) and subsequently converted by *Nitrobacter* spp. into nitrate (NO_3^-). Plants absorb nitrate as a nutrient source, thus contributing to water purification and allowing clean water to be recirculated back to the fish

By integrating three distinct biological groups—fish, bacteria, and plants—aquaponics emerges as a viable solution for sustainable food production, characterized by enhanced productivity and reduced ecological impact [80, 81, 84]. Recent studies also highlight the potential of aquaponics as an innovative model for indoor production systems, emphasizing its dual advantage: the reduction of environmental impact through wastewater biofiltration and the increase in economic profitability through the simultaneous valorization of fish and crop production [88]. Nonetheless, large-scale implementation depends on the integration of advanced technologies, the optimization of techno-biological performance, and the reduction of operational costs—factors essential for the transition toward resource-efficient and sustainable aquaculture systems [89]. Traditional practices, such as the fish-cum-rice system, where fish are reared concurrently with rice cultivation, provide clear examples of the effective integration of aquatic and plant components within a common agricultural framework. These systems allow for the sustainable valorization of nutrients and water resources, contributing to optimized productivity and reduced ecological impact [15]. Along these lines, the integration of common carp (*Cyprinus carpio*) with basil (*Ocimum basilicum*) in an aquaponic system has demonstrated a functional balance between fish growth and plant development. Water quality was maintained

within optimal ranges for nitrification, thus simultaneously supporting fish welfare and promoting efficient nutrient uptake by plants [90, 91]. The rearing of tilapia (*Oreochromis* sp.) together with lettuce (*Lactuca sativa*) in a freshwater IMTA system showed enhanced biological performance for both species, particularly when the fish diet was supplemented with an organic–inorganic blend, which also improved the efficiency of nutrient bioremediation [92]. Moreover, the protein source used in the diet of Nile tilapia (*Oreochromis niloticus*) was found to affect the composition of recirculated water in RAS, with direct effects on the yield and quality of hydroponically grown crops such as lettuce (*Lactuca sativa*) and basil (*Ocimum basilicum*) within integrated systems [93].

The rearing of Atlantic salmon (*Salmo salar*) at the freshwater juvenile stage in an integrated multitrophic aquaculture (IMTA) system, alongside plant species such as lettuce (*Lactuca sativa*), mint (*Mentha* sp.), chamomile (*Matricaria chamomilla*), and watercress (*Nasturtium officinale*), demonstrated the potential of aquaponics to reduce residual nutrients and diversify plant production, thereby supporting the applicability of this model in commercial hatchery facilities [94].

Similarly, the integration of tilapia (*Oreochromis* sp.) with tomato (*Solanum lycopersicum*) in a recirculating aquaponic system housed within a greenhouse demonstrated the efficient reuse of

water and nutrients. Effluent from the fish tanks was used to irrigate 890 hydroponically grown tomato plants, requiring only moderate mineral supplementation. Moreover, the use of a low-sodium, plant-based feed reduced the risk of Na⁺ accumulation and enhanced overall system efficiency, supporting a circular resource-value-valorization strategy [95].

The co-culture of pikeperch (*Sander lucioperca*) with lettuce (*Lactuca sativa*) in a recirculating aquaponic system demonstrated the efficient reuse of nutrients from fish effluents, supporting the simultaneous production of both fish and vegetables. Compared with conventionally grown lettuce, plants produced in the integrated system exhibited significantly higher nitrate concentrations, while remaining within established food-safety thresholds. This co-culture model demonstrates the potential of aquaponics as a sustainable solution for valorizing organic compounds derived from aquaculture operations [96].

In a freshwater integrated multitrophic system combining African catfish (*Clarias* sp.) culture with the cultivation of duckweed (*Lemna* sp.), the implementation of a waste stabilization pond (WSP) structure, comprising anaerobic, facultative, and maturation ponds, resulted in significant improvements in water quality. These were reflected in increased dissolved oxygen and reductions in nitrogen and phosphorus compounds, thereby supporting the sustainable functioning of the system [51].

The integration of pond-based fish farming with agricultural activities, such as Chinese cabbage (*Brassica rapa chinensis*) or rice (*Oryza sativa*), has been evaluated in combined polyculture systems employing freshwater species including African catfish (*Clarias gariepinus*), Nile tilapia (*Oreochromis niloticus*), silver barb (*Puntius gonionotus*), and common carp (*Cyprinus carpio*). Results highlighted substantial economic benefits, reflected in increased fish and crop yields and higher annual farmer incomes, confirming the viability of these integrated models for small-scale agriculture [97, 98].

Co-culture between Fish and Crustaceans

The co-culture of fish and crustaceans represents only one of the many possible configurations within integrated multitrophic aquaculture (IMTA) systems, which are designed to combine species from different trophic levels in order to

valorize the waste generated by fed organisms and thereby enhance both the economic and ecological sustainability of aquaculture. IMTA principles are not confined to marine ecosystems; they are equally applicable to closed freshwater systems, provided that species are selected for trophic and economic compatibility [20, 54, 99]. A concrete example is the integration of Nile tilapia (*Oreochromis niloticus*) with Amazon river prawn (*Macrobrachium amazonicum*) in static ponds, where phosphorus-use efficiency has been shown to depend on periphyton development and the proportion of submerged surface area, even though substrate addition did not lead to significant phosphorus retention in animal biomass [100].

This approach is further supported by results from the co-culture of tambaqui (*Colossoma macropomum*) with Amazon river prawn (*Macrobrachium amazonicum*) in earthen-pond IMTA systems. These systems demonstrated improved nutrient recovery and stable water quality by converting organic waste into harvestable biomass and reducing excess nutrient loads. In addition, the accumulation of sedimentary organic matter with potential agricultural use offers opportunities for circular-economy applications. Nevertheless, a considerable share of nutrients remains stored in sediments or lost through denitrification, underscoring the need for further research on sedimentary carbon availability, nitrogen and phosphorus fluxes, and the role of bioturbation. The inclusion of detritivorous or ilyophagous species may represent an effective strategy to maximize nutrient recycling and improve overall system efficiency [101-103].

Extending these practices to fish–crustacean co-culture provides new opportunities for diversifying IMTA systems. Recent studies have shown that the noble crayfish (*Astacus astacus*) can be efficiently co-cultured with hybrid striped bass (*Morone chrysops* × *Morone saxatilis*) in freshwater systems, exhibiting significant weight gain and carapace development when fed fish feces. By contrast, the Turkish crayfish (*Pontastacus leptodactylus*) is not recommended for co-culture with European pikeperch (*Sander lucioperca*) due to poor growth performance and variability in RNA/DNA ratios, which limits the usefulness of this biomarker for assessing physiological condition under suboptimal feeding regimes [104].

A complementary example is the co-culture of Nile tilapia (*Oreochromis niloticus*) and red claw crayfish (*Cherax quadricarinatus*) in biofloc systems, which showed that increasing the carbon-to-nitrogen (C:N) ratio improves feed-use efficiency and water quality without significantly affecting total biomass or growth rates, underscoring the potential of adjusting this parameter for sustainable production [105].

The co-culture of Nile tilapia (*Oreochromis niloticus*) and giant freshwater prawn (*Macrobrachium rosenbergii*) in Biofloc Technology (BFT) and Recirculating Aquaculture Systems (RAS) revealed superior performance in BFT—an intensive system that recycles nutrients through microbial bioflocs—reducing water consumption and improving water quality. In this context, feed conversion efficiency was higher, and prawn survival reached 87% in BFT compared with 79% in RAS, highlighting the advantages of this technology for integrated and sustainable aquaculture [106].

In resource-limited countries such as Bangladesh, periphyton-based pond systems have proven effective in enhancing primary productivity and natural food availability, particularly in the co-culture of Nile tilapia (*Oreochromis niloticus*) with giant freshwater prawn (*Macrobrachium rosenbergii*). This practice is recognized as both technically feasible and economically viable [107].

In India, polyculture trials in earthen ponds have combined cyprinid species with complementary trophic niches—catla (*Catla catla*), rohu (*Labeo rohita*), and mrigal (*Cirrhinus mrigala*)—with giant freshwater prawn (*Macrobrachium rosenbergii*), aiming to optimize feeding regimes and water management protocols. These integrated systems delivered higher yields and promoted more sustainable use of natural resources [108, 109].

Co-culture of Fish, Crustaceans, and Plants

The integration of aquatic plants such as water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), and duckweed (*Lemna minor*), plays a pivotal role in wastewater treatment by effectively removing inorganic nutrients and reducing pollutant loads from wastewater and polluted aquatic sources. Incorporating these extractive macrophytes into freshwater IMTA systems highlights the benefits of co-cultivating fish, freshwater crustaceans, and aquatic plants

[110]. At the same time, the harvested plant biomass can be valorized through conversion into eco-friendly composite materials, thereby supporting circular-economy goals and reducing waste volumes [111].

This integrative approach is also supported by studies on recirculating aquaponic systems in which fish and crustaceans are co-cultivated with hydroponic vegetables. For example, the co-culture of Nile tilapia (*Oreochromis niloticus*) and giant freshwater prawn (*Macrobrachium rosenbergii*) in a recirculating system supporting lettuce (*Lactuca sativa*), Chinese cabbage (*Brassica rapa pekinensis*), and pak choi (*Brassica rapa*) has shown that increased biological diversity through multi-species integration contributes to the ecological stabilization of the system and can enhance plant yields. Although limitations related to elevated pH and low concentrations of dissolved nutrients have been reported, the tri-trophic integration of fish, crustaceans, and plants allows for more efficient resource utilization, supporting the applicability of this model, including in urban contexts [112].

Co-culture of Fish and Bivalves

The integration of filter-feeding organisms, such as bivalves, within IMTA systems not only utilizes organic waste but also reduces the risk of disease by removing particulate matter and pathogenic microorganisms from the water column, thereby providing both ecological and economic benefits to aquaculture [113].

A particularly promising avenue is the co-culture of fish with bivalves in freshwater systems. For instance, the swan mussel (*Anodonta cygnea*), when integrated into fishponds, makes use of fish-derived waste, contributing to biological water purification and reducing economic losses in line with circular-economy principles [114].

Similarly, the endemic Chilean freshwater mussel *Diplodon chilensis* has been shown to significantly lower concentrations of chlorophyll-a, phosphates, and ammonia in aquaculture effluents, underscoring the vital role of freshwater bivalves in bioremediation processes [115].

Further illustrating this potential, the co-culture of rainbow trout (*Oncorhynchus mykiss*) with the Chinese freshwater mussel (*Sinanodonta woodiana*) in indoor recirculating aquaculture systems achieved reductions of up to 72% in total bacterial load and 95–98% in the pathogen *Aeromonas hydrophila*. These findings

demonstrate that freshwater bivalves can serve not only to improve water quality but also as effective biotechnological tools for reducing microbiological risks and antibiotic resistance in aquaculture [49].

Co-culture of Fish, Bivalves, and Plants

The integration of fish, bivalves, and plants within freshwater IMTA systems offers an effective alternative for optimizing nutrient cycling and fully utilizing available resources. A relevant example is the co-culture of Nile tilapia (*Oreochromis niloticus*), thinlip mullet (*Liza ramada*), and silver carp (*Hypophthalmichthys molitrix*) together with the freshwater bivalve *Aspatharia chaiziana* and various extractive plant species, such as lettuce (*Lactuca sativa*), bell pepper (*Capsicum annuum*), cucumber (*Cucumis sativus*), and celery (*Apium graveolens*). This trophic association supports a circular and resilient aquaculture model in which productivity is enhanced and waste is transformed into valuable resources, thereby contributing to sustainable inland aquaculture [47].

Co-Culture of Fish, Crustaceans, Bivalves, and Plants

The integration of Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*), thinlip mullet (*Liza ramada*), freshwater prawns (*Macrobrachium rosenbergii*), unionid mussels (*Unio* spp.), and hydroponically grown vegetables—such as lettuce, broccoli, cucumber, tomato, eggplant, and both sweet and hot peppers—within an IMTA-aquaponic system resulted in improved nutrient utilization efficiency and enhanced water quality. This model provides a sustainable and productive alternative for inland aquaculture, with ecological and economic benefits, particularly in resource-limited regions [116].

4. Conclusions

Integrated Multi-Trophic Aquaculture (IMTA) represents an innovative and sustainable solution for modern aquaculture development, harnessing the interactions among fish, crustaceans, bivalves, and plants. By recycling nutrients and reducing waste, IMTA optimizes resource use and improves water quality, thus contributing to environmental protection.

These systems enable production diversification and the creation of value-added products, while remaining fully aligned with circular-economy principles and the Sustainable Development Goals. Their implementation across different aquaculture forms, from earthen ponds to recirculating systems, demonstrates their flexibility and applicability under a wide range of conditions.

In conclusion, IMTA is not only a viable option but also a future direction for sustainable, efficient, and responsible aquaculture, adapted to today's challenges of limited resources and environmental demands.

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