İSTANBUL UNIVERSITY PRESS

EISSN 2602-473X

AQUATIC SCIENCES AND ENGINEERING

Aquat Sci Eng 2023; 38(2): 106-121 • DOI: https://doi.org/10.26650/ASE20231252136

Review Article

Application of the IMTA (Integrated Multi-Trophic Aquaculture) System in Freshwater, Brackish and Marine Aquaculture

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Cite this article as: Azhar, M.H., & Memis, D. (2023). Application of the IMTA (integrated multi-trophic aquaculture) system in freshwater, brackish and marine aquaculture. *Aquatic Sciences and Engineering, 38(2), 106-121.* DOI: https://doi.org/10.26650/ASE20231252136

ABSTRACT

Aquaculture activities that have been carried out intensively for several decades have made this sector grow rapidly compared to other food sectors. However, intensive activities have negative impacts, one of which is on the environment. To respond to these problems, aquaculture activities have now focused on environmentally friendly aquaculture by implementing various ecosystem-based cultivation systems and improving aquaculture management based on the principle of sustainable aquaculture. The IMTA (Integrated Multi-trophic Aquaculture) system is a cultivation system that uses species with different trophic levels to reuse wasted nutrients to be used as biomass. Currently, the IMTA system has begun to be developed in various countries in fresh, brackish, and marine water cultivation with multiple approaches according to environmental, social, and economic conditions. This review study discusses different IMTA systems and their applications.

Keywords: Ecosystem Approach Aquaculture; Aquatic Sustainable Aquaculture; Integrated Multi-Trophic Aquaculture (IMTA)

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Submitted:
17.02.2023

Revision Requested:
05.04.2023

Last Revision Received:
09.04.2023

Accepted:
18.04.2023

Online Published:
05.05.2023

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INTRODUCTION

Aquaculture has been one of the fastest-growing sectors in recent years. In 2015, 53% of total fishery production came from aquaculture. In addition, aquaculture production is predicted to increase by 32% (around 26 million tons) or reach approximately 109 million tons in 2030 (FAO, 2018). To meet the increasing market demand, intensive aquaculture activities are carried out. However, there are significant challenges faced by the aquaculture sector where producing organisms still use too many natural resources and impact the environment (Martinez-Porchas & Martinez-Cordova, 2012). In addition, the impact of intensive aquaculture practices creates several problems for the environment. One of the main problems caused is the nutrient load from metabolic waste products and uneaten feed (Tacon et al., 2010; Troell et al., 2017a). Nutrient loads that are wasted into the environment can cause eutrophication, ecosystem damage, biodiversity loss, and decreased oxygen concentration and water quality (Diana et al., 2013; Edwards, 2015; Martinez-Porchas & Martinez-Cordova, 2012). To deal with these problems, it is necessary to implement an environmentally friendly, ecosystem-based cultivation system and improve aquaculture management based on sustainable aquaculture.

Sustainable aquaculture, according to FAO (1995), is an economical and socially acceptable aquaculture activity based on the conservation of natural resources using technology. Sustainable aquaculture is a solution to dealing with the negative impacts of current aquaculture activities. Sustainable aquaculture must be ecologically efficient, environmentally friendly, diverse in products, and economically and socially profitable (Chopin, 2013a). To realise sustainable aquaculture, several criteria must be carried out: aquaculture activities must 1) promote socio-economic aspects, 2) produce and provide safe and nutritious products, 3) increase fish production in terms of land use, water, feed, and energy used, 4) and minimise water pollution, fish disease, and fish escaping into nature (Waite et al., 2014).

The development of cultivation with the concept of sustainability is currently being widely applied. Methods include using a recirculation system (RAS) and an eco-friendly and ecosystem-based cultivation system that has been implemented, one of which is through the multitrophic concept (IMTA). The RAS system (Recirculating Aquaculture Systems) is one of the technologies developed for intensive aquaculture. The RAS system allows the use of 90-99% of the water that has been recycled using specific components. However, this system has several limitations, including greater energy use, high production costs, waste disposal problems, and a high risk of failure due to disease (Badiola et al., 2012). The RAS system is currently only used in aquaculture activities with high selling value, definite production protocols, and large production models for mass-scale efficiencies, such as salmon and shrimp. So the cultivation of the RAS system with other cultivation systems still needs to be determined (Naylor et al., 2021). Meanwhile, multitrophic cultivation (IMTA) develops from the traditional polyculture cultivation model, as well as fish or shrimp farming which is integrated with vegetable plants, microalgae, shellfish, and seaweed. This system has been implemented for the past few decades, especially in Asia (Neori et al., 2004).

History of IMTA

The IMTA concept has been under development for a long time. It is based on the book Nong Zheng Quan Shu (The Complete Book on Agriculture), written in 1639, which explains many topics in the agricultural sector, including irrigation and rotation of fish and plant production in a field, integrated cultivation between fish and livestock, the use of manure for fish farming, as well as integrated cultivation of mulberry, paddy fields, and fish ponds (Chopin, 2013b). Modern IMTA began to develop in 1970 when John Ryther, through a project called "integrated waste-recycling marine polyculture systems", tried to revive the IMTA concept in modern times by developing intensive methods of processing waste outlets using seaweed and Bivalvia (Troell et al., 2003). Then in the 2000s, this concept was applied to aquaculture through various modifications such as polyculture cultivation, integrated marine cultivation, and ecology-based aquaculture (Kodama, 2019; Chopin, 2013b). Then, in 2004, the term *integrated multitrophic aquaculture* emerged and was initiated by Thierry Chopin and Jack Taylor. The basic concept of the IMTA system is the conversion of nutrients produced from aquaculture activities through species diversification (Chopin, 2013b).

IMTA System definition and principles

The IMTA is a cultivation system that utilises species with different eating habits and trophic levels in the same production system. These species are placed in the same compartments or separately in the waste stream (Figure 1). The goal is to be able to utilise waste that is reusable (Barrington et al., 2009; Chopin et al., 2008; Chopin et al., 2013). The IMTA system adheres to the "circular principle". In this system, scientific integration occurs in the utilisation of uneaten feed, waste, nutrients, and by-products produced by the species being fed for conversion into fertiliser, feed, and energy by other species with lower trophic levels (FAO, 2022). The selection and proportion of the use of correct species will balance the biological and chemical processes in the IMTA system. In addition, species use serves as a biofilter, and the species can be harvested and has commercial value (Chopin, 2006). The IMTA system generally aims to improve the ecosystem's condition in the cultivation environment and produce more excellent cultivation production than the monoculture model (Neori et al., 2004).

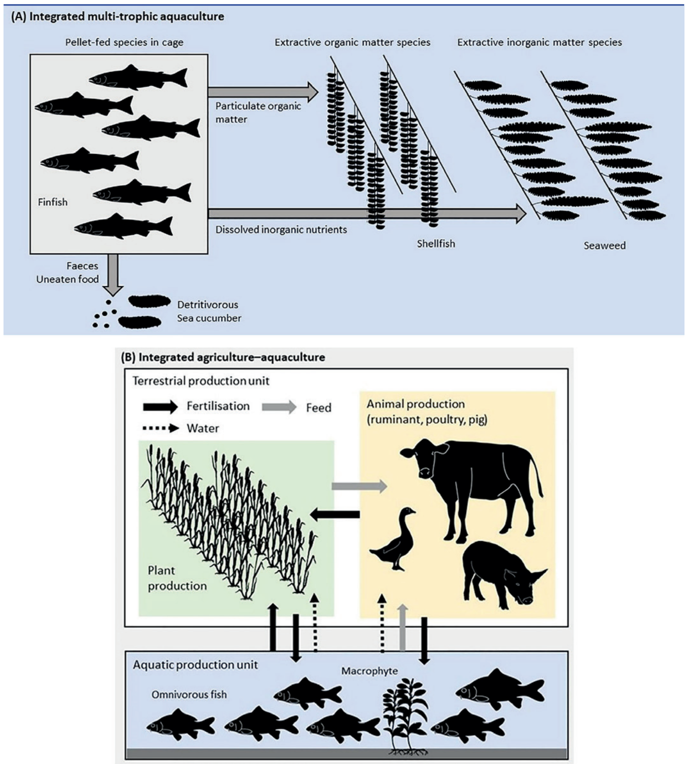

Figure 1. IMTA system concept (Thomas et al., 2020).

Components of the IMTA System

Several essential components in the IMTA system need attention, including species selection, extractive species (*organic and inorganic extractive species*), main species (*fed aquaculture*), and the IMTA design (Sasikumar & Viji, 2015). Species selection will affect cultivation with the IMTA system. The use of the suitable species will affect a stable and sustainable environmental balance, improve the environment, and increase total production (Chopin, 2006; Rosa et al., 2020; Sanz-Lazaro & Sanchez-Jerez, 2020).

Several criteria must be considered in species selection. The selected species must be able to complement each other with other species in a system based on the tropic level so that nutrients can be efficiently produced and able to increase production (Barrington et al., 2009; Khanjani et al., 2022; Sasikumar & Viji, 2015). The selected species must have a good level of adaptation, preferably come from local species, and have a high level of production (Largo et al., 2016). Attention must be paid to cultivation technology and environmental conditions; the selected species have the ability to improve ecological conditions efficiently (bio-mitigation) and sustainably (Sasikumar & Viji, 2015). Finally, species that meet market demand and have commercial value must be used (Carras et al., 2020).

The components of the IMTA system relate to the utilisation of nutrients from each trophic level. The route of nutrient utilisation can be seen in Figure 2. The existence of extractive species (organic and inorganic) has a vital role in the IMTA cultivation system. Extractive species are species that can utilise and reduce waste in the form of organic matter (particulates and suspensions) and dissolved inorganic matter originating from metabolism (ammonium (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}) and carbon dioxide (CO_2), as well as other by-products derived from main species (fed species) to be used as a source of energy for growth (Barrington et al., 2009; Chopin, 2006; Reid et al., 2018; Rosa et al., 2020). In addition, organic extractive species which function as secondary consumers are also marketable, although this is not an essential factor (Sasikumar & Viji, 2015).

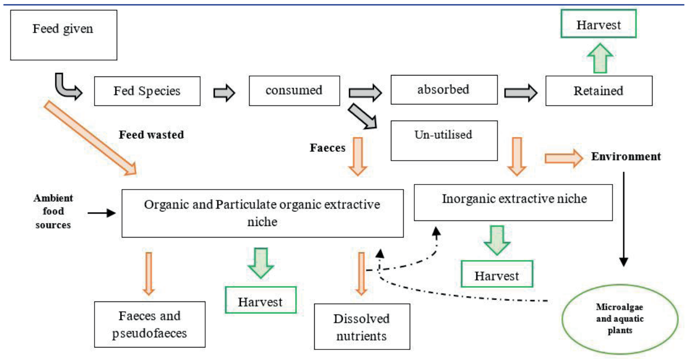

Figure 2. Routes of transfer of nutrients from fed species to extractive species. The black arrows show the nutrient flow of the species being fed. The orange arrows indicate the flow of nutrients extractive species use in addition to those from nearby food sources. The green arrows show the flow of nutrients into biomass during harvesting. Dashed arrows indicate an indirect relationship in nutrient utilisation (Reid et al., 2018).

The use of organic extractive species in IMTA can come from species that act as suspension or deposit feeders. Types of organic extractive species commonly used in the IMTA system include those from the Mussels group. However, several other species have been tried, as seen in the studies by Giangrande et al. (2020), Jerónimo et al. (2020), and Nederlof et al. (2019), who used deposit feeder species from the Polychaetes group and sponges. The results show that using species can increase waste utilisation, efficiency, and profitability (Giangrande et al., 2020). Aquatic plants are inorganic extractive species in the components of the IMTA system that utilise nutrients that are wasted in water (C, N, and P). Through the process of photosynthesis, aquatic plants will form new biomass and cause the formation of a mini ecosystem in the cultivation system (Sasikumar & Viji, 2015). Some inorganic extractive species include seaweed, which is generally used in mariculture cultivation with the IMTA system. Seaweed is used because it can absorb nutrients from cultivation activities or from outside that enter through the exchange of water flows (Yokoyama, 2013).

Fed species is the main component in aquaculture because it is the only component fed to aquaculture with the IMTA system. In this system, fish are the primary source of nutrition for other organisms. Nutrient retention from fed species is influenced by the type and size of fish used, feed composition and management, and environmental factors (Schneider et al., 2005). Fish is the primary source of income in IMTA system cultivation. Therefore, it is necessary to select profitable and marketable fish species. In addition, the selection of fish species and type of feed will also affect the quantity and quality of waste generated in the IMTA system (Sasikumar & Viji, 2015).

The exemplary system design will affect the effectiveness and success of cultivating the IMTA system. The method of the IMTA system must pay attention to the placement, arrangement, and selection of species to be used. System design and species selection must be engineered so that organisms with lower multi-trophic levels can utilise the waste from aquaculture activities optimally (Sasikumar & Viji, 2015).

Selection of Extractive Species in the IMTA System

Production of extractive species increased significantly compared to 2000, with a percentage of 43% live weight of total world aquaculture production in 2017 (Naylor et al., 2021). This production increase is generally used for non-food products and ecosystem improvement. Several extractive species are commonly used in the IMTA system, including crustaceans, mussels, sea cucumbers, Polychaeta, sponges, and seaweed (Figure 3) (Granada et al., 2016; Khanjani et al., 2022; Zhang et al., 2019).

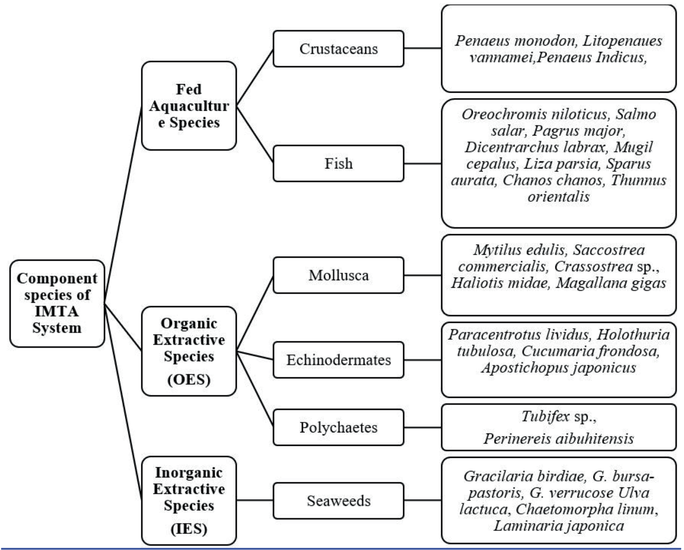

Figure 3. Common types of species used in IMTA cultivation (adapted from Khanjani et al., 2022; Nissar et al., 2023; Zhang et al., 2019).

The selection of suitable extractive species is crucial in supporting success in cultivation with the IMTA system. In general, the use of extractive species in the IMTA system aims not only to improve environmental conditions but also to provide additional benefits such as minimising the risk of failure during the cultivation process, having commercial value, complying with market demand and being accepted by the community (Barrington et al., 2009; Chopin, 2006; Granada et al., 2016). The use of extractive species must also pay attention to growth rates, densities, characteristics, seasonal cycles, and comparison ratios between species, as well as the use of local species that aim to facilitate adaptation and reduce the risk of using introduced species (Ren et al., 2012). Another thing that needs to be considered in selecting extractive species is understanding habitat specifications, because this will affect the growth of the species used (Barrington et al., 2009). With the growing development of IMTA cultivation in the world, the use of potential new species has begun to be tried in several IMTA studies in fresh, brackish, and marine water cultivation (Tables 1 and 2).

Freshwater IMTA

The concept of freshwater IMTA or FIMTA (freshwater IMTA) has long been practised in freshwater aquaculture, especially in Asia countries (Chopin 2013a). Freshwater aquaculture using the IMTA system generally uses tilapia and carp (Bakhsh & Chopin, 2012; Kestemont, 1995). In addition, the application of the IMTA system in freshwater aquaculture is more common in tropical climates than in cold or temperate climates. This is due to differences in water temperature (Bakhsh et al., 2015). Along with the development of increasingly modern aquaculture, FIMTA is also being developed. Aquaponics is one variation of freshwater IMTA cultivation that is currently widely applied (Chopin et al., 2016). Aquaponics is one part of the IMTA system because it utilises at least two species, such as fish and plants. The two species use nutrient sources and have different roles in aquatic ecosystems (Bakhsh & Chopin, 2012; White et al., 2004). Several FIMTA studies have been conducted, as shown in Table 3.

The results from several FIMTA studies show that the IMTA system can improve environmental conditions for cultivation and increase overall biomass production through product diversification. Several things still need to be studied in implementing the FIMTA system, including understanding the flow of nutrients in the system, using local species in the IMTA system, and the proportion of species used.

Marine and Brackish Water IMTA

IMTA is a flexible system and can be developed based on environmental, social, and economic conditions in the area where it is implemented. In addition, the IMTA system can be applied to freshwater, brackish, marine, open-water, and land-based aquaculture activities in temperate to tropical climates (Chopin 2013b). Applying the IMTA system to marine systems is a cultivation model for

Table 1. Several types of species used in Freshwater IMTA.

Fed species	Organic extractive species	Inorganic extractive species
Oreochromis niloticus		*Lactuca sativa*
Anabas testudineus Blk. *Oreochromis niloticus*	*Tubifex* sp.	*Ipomoea reptana* *Brassica juncea,* *Ocimum basiliucum*
Oreochromus niloticus *Clarias gariepinus* *Liza ramada*	*Macrobrachium rosenbergii* *Aspatharia chaiziana* *A. marnoi*	*Brassica oleracea* *Cucumis sativus* *Lactuca sativa* var. *capitata* *Lactuca sativa crispa* *Solanum lycopersicum* *Solanum melongena* *Capsicum annuum*
Salmo salar		*Nasturtium officinale* *Lactuca sativa* *Beta vulgaris cicla* *Allium schoenoprasum* *Cichorium endivia* *Solanum lycopersicum* *Tagetes patula* *Tropaeolum majus* *Achillea millefolium* *Matricaria chamomilla* *Mentha* sp.
Oreochromis niloticus	*Macrobrachium amazonicum*	
Catla catla *Hypophthalmichthys molitrix* *Labeo rohita* *Cirrhinus mrigala* *Heteropneustes fossilis*	*Viviparus bengalensis*	*Ipomoea aquatica*

Table 1. Continue.

Fed species	Organic extractive species	Inorganic extractive species
Cyprinus carpio *Rutilus rutilus* *Tinca tinca*		*Nuphar lutea* *Mentha aquatica* *Typha latifolia* *Glyceria aquatica* *Ceratophyllum demersum* *Phalaris arundinacea*
Colossoma macropomum	*Macrobrachium amazonicum*	
Colossoma macropomum	*Macrobrachium amazonicum* *Prochilodus lineatus*	
Cyprinus carpio *Rutilus rutilus* *Tinca tinca*		*Ceratophyllum demersum* *Glyceria aquatica* *Nuphar lutea* *Nasturtium officinale* *Pondeteria cordata*
Labeo rohita	*Lamellidens marginalis*	*Wolffia globose*
Oncorhynchus mykiss *Perca fluviatilis*		*Lemna minor* *L. minor* Keywaters *L. gibba.*
Oreochromis niloticus	*Liza ramada* *Procambarus clarkia* *Aspatharia chaiziana* *Hypophthalmichthys molitrix*	*Lactuca sativa crispa* *Capsicum annuum* *Cucumis sativus* *Solanum melongena* *Althea Officinalis* *Nasturtium officinale* *Apium graveolens*

References: (Bakhsh & Chopin, 2012; Chopin et al., 2016; David et al., 2017; Flickinger et al., 2019a; Flickinger et al., 2020; Flickinger et al., 2019b; Franchini et al., 2020; Goada et al., 2015; Ibáñez Otazua et al., 2022; Jaeger & Aubin, 2018; Jaeger et al., 2021; Kibria & Haque, 2018; Nath et al., 2021; Paolacci et al., 2021)

Table 2. Several types of species used in marine-brackish water IMTA studies.

Fed species	Organic extractive species	Inorganic extractive species
Crassostrea gigas	*Apostichopus japonicus*	
Litopenaeus vannamei		*Gracilaria tikvahiae*
Sparus aurata	*Mugil cephalus*	
Litopenaeus vannamei		*Gracilaria birdiae*
Pseudosciaena crocea		*Gracilaria lemaneiformis*
Sparus aurata		*Ulva lactuca*
Sparus aurata *Paracentrotus lividus*		*U. lactuca*
Argyrosomus regius *Diplodus sargus*	*Mugil cephalus* *Crassostrea gigas*	Microalgae (Naturally developed in ponds/ *Tetraselmis* spp.) *Ulva* sp.
Dicentrarchus labrax	*Crassostrea gigas*	Microalgae (*Tetraselmis* sp., *Stauroneis* sp. *Phaeodactylum* sp.)
Litopenaeus vannamei	*Mugil liza*	
Litopenaeus vannamei	*Mugil liza*	
Mugil cephalus *Liza parsia*	*Crassostrea cuttackensis*	*Ipomoea aquatica*
	Sarcotragus spinosulus *Sabella spallanzanii* *Mytilus galloprovinciali*	*Chaetomorpha linum* *Gracilaria bursa-pastoris*
Hexagrammos otakii	*Perinereis aibuhitensis*	

Table 2. Continue.

Fed species	Organic extractive species	Inorganic extractive species
Litopenaeus vannamei		*Agarophyton tenuistipitatum*
	Holothuria scabra *Anadara antiquata*	
Litopenaeus vannamei	*Crassostrea* sp.	
Penaeus monodon	*Anadara granosa*	*Gracilaria verrucose*

References: (Amalia et al., 2022; Biswas et al., 2019; Borges et al., 2020; Brito et al., 2016; Cunha et al., 2019; Giangrande et al., 2020; Holanda et al., 2020; Hu et al., 2021; Li et al., 2019; Lima et al., 2021; Magondu et al., 2022; Samocha et al., 2015; Sarkar et al., 2021; Shpigel et al., 2016; Shpigel et al., 2017; Shpigel et al., 2018; Wei et al., 2017; Yokoyama, 2013)

Table 3. Study research with fresh water IMTA system (FIMTA).

Treatments	Parameters	Conclusions and recommendations	References
Use of inorganic and organic nutrients with different concentrations with a maintenance period of 45 days.	-Growth performance: feed conversion ratio (FCR), absolute growth rate (AGR), specific growth rate (SGR), survival rate (SR), weight gain (WG), protein efficiency ratio (PER), and total plant yield (TPY)). -Water quality: water temperature, pH, dissolved oxygen (DO), nitrate (NO_3^-), and phosphate (PO_4^{3-}). -Proximate analyses: crude protein, crude fibre, crude lipid, ash, and moisture of feed and fish.	The use of tilapia and lettuce positively responded to feed enriched with organic-inorganic materials.	(Bakhsh & Chopin, 2012)
The use of different types of inorganic extractive species with a maintenance period of 32 days.	-Water quality: pH, DO, alkalinity, carbon dioxide (CO_2), total ammonia nitrogen (TAN), NO_3^-, and PO_4^{3-}.	The extractive species can adsorb TAN by 86.5% and increase fish biomass to 62.69 kg m^{-3}.	(Sumoharjo & Maidie, 2013)
Use of two different IMTA-integrated aquaponics systems (NFT and FRS systems) with a maintenance period of 2 periods (2 years).	-Water quality: water temperature, pH, DO, ammonia (NH_3^+), nitrite (NO_2^-), nitrate (NO_3^-), alkalinity, and electrical conductivity (EC). -Growth performances: mean final body weight (FBW), SGR, and FCR. -Economic analysis: operating ratio, return on revenue, ratio of income to costs, capital payback period, and return on equity.	The IMTA-FRS (Floating Raft system) is a good model for small-scale businesses with a payback investment period ranging from 2.17-3.34 years.	(Goada et al., 2015)
The utilisation of various types of inorganic extractive species in salmon hatcheries.		The ability of extractive species to absorb nutrients depends on the type of species used, the amount of biomass produced, and the nutritional level of the waste produced.	(Chopin et al., 2016)
The use of different substrates in rearing tilapia, which is integrated with shrimp, with a maintenance period of 140 days.	-Water quality: water temperature, DO, pH, TAN, NO_2^-, NO_3^-, transparency, and total suspended solids (TSS). -Growth performances: SR, individual mean weight, and productivity. -Nitrogen budget.	-Using different substrates does not increase nitrogen retention in fish and shrimp. -Recovery of Nitrogen in ponds depends on periphyton development and substrate cover area. -The application of integrated aquaculture in stagnant ponds can absorb most of the nitrogen from the culture media.	(David et al., 2017)

Table 3. Continue.

Treatments	Parameters	Conclusions and recommendations	References
The use of a combination of different extractive species in carp and stinging catfish cultivation in a cage-cum-pond model maintained for six months.	-Water quality: Temperature, pH, DO, NH_3^+, NO_2^-, and PO_4^{3-}. -Growth performances: percent weight gain, SGR, FCR. -Yield estimation: gross yield of fish and total yield.	Using species diversification can increase productivity and maintain water quality balance.	(Kibria & Haque, 2018)
Use of pond models with different systems with a maintenance period of 7 months.	-Water quality: water temperature, pH, DO, oxygen saturation, EC, redox potential, transparency, and nutrient concentrations (N and P) in water and sediments. -Growth performance: SR, SGR, and FCR. -Biological parameters: chlorophyll-a, total chlorophyll, blue, green, and brown chlorophyll.	-The use of plants in carp, roach, and tench co-culture made the water quality better and more stable (pH and oxygen) in spring and summer compared to other treatments (extensive and semi-intensive ponds). The use of plant ponds can also store P in the sediment properly. -Research on the economical use of macrophytes and exploration studies on biodiversity (zooplankton and macro-invertebrates); the nutrition cycle of the feed of each cultivated species needs to be done.	(Jaeger & Aubin, 2018)
Integrated maintenance between tambaqui-prawn in earthen ponds with different production systems was carried out for 171 days.	-Water quality: water temperature, pH, DO, oxygen saturation, EC, total nitrogen (TN), TAN, NO_2^-, total phosphorus (TP), and transparency. -Biological parameter: chlorophyll-α. -Phosphorus budget	-Using species with different tropic levels can increase productivity and more efficient phosphorus uptake ranging from 24-34%, converted into harvestable biomass products. -There is a need for further studies on using phosphorus as waste from aquaculture activities and adding other detritivores and hylophagous (mud-eating) species.	(Flickinger et al., 2019a)
Integrated rearing between tambaqui-prawn in earthen ponds with different production systems was carried out for 171 days of maintenance.	-Water quality: water temperature, pH, DO, Oxygen Saturation, EC, TN, TAN, NO_2^-, TP, and transparency. -Biological parameter: chlorophyll-α. -Nitrogen budget.	-Fish-prawn cultivation using the IMTA system is more efficient in utilising nitrogen from feed into harvested biomass than monoculture. -Further studies on the flow of nitrogen and sediment in ponds and the bottom soil need to be carried out. It is necessary to study the effect of the bioturbation of cultivated species on the biological processes that occur in the bottom sediments.	(Flickinger, et al., 2019b)
Integrated rearing between tambaqui-prawn in earthen ponds with different production systems was carried out for 171 days of maintenance.	-Water quality: water temperature, pH, DO, oxygen saturation, EC, TN, TAN, NO_2^-, TP, and transparency.-Biological parameter: chlorophyll-α.-Carbon budget.	-The IMTA system can maintain water quality in acceptable conditions and improve the cultivation system with earthen ponds by producing organic matter that settles to be used as fertiliser for other agricultural activities. -The need for further research on the bioavailability of organic carbon accumulated in settled solids, silt, and the water column.	(Flickinger et al., 2020)

Table 3. Continue.

Treatments	Parameters	Conclusions and recommendations	References
The use of a combination of extractive species was carried out for 53 days of the rearing period.	-Growth performances: SR, total length, body mass, body mass gain, FCR total, and total yield.-Water quality: water temperature, DO, EC, pH, TAN, TP, and chlorophyll-a.	-The use of curimbata can increase biomass production and efficiency of feed utilisation. -This study also shows that the integrated cultivation of tambaqui, amazon river prawn, and curimbata is feasible, especially in the nursery phase. -Further studies are focused on stocking density and the proportion of each species based on its growth phase.	(Franchini et al., 2020)
Use of lagoon plants in semi-intensive coupled (fishpond and lagoon) model, semi-intensive with water movement, and extensive fishponds.	Growth performances: Condition Factor (K), SR, SGR, and FCR.	Nutrients from aquaculture ponds can increase primary and invertebrate production, providing additional natural food for cultivated fish species. In addition, it can maintain water quality conditions in optimal conditions.	(Jaeger et al., 2021)
Co-culture maintenance with a combination of different extractive species with a maintenance period of 90 days.	-Water quality: transparency, ph, total alkalinity, hardness, NH$_3^+$, NO$_2$, NO$_3^-$, and PO$_4^{3-}$. -Growth performances: SR, daily growth index (DGI), daily weight gain (DWG), net fish yield (NFY), apparent feed conversion ratio (AFCR), apparent protein efficiency ratio (APER), and apparent protein retention (APR). -Biological parameters: hemoglobin (Hb), erythrocytes (RBC), and leucocytes (WBC). -Immunological responses: nitroblue tetrazolium (NBT) and total myeloperoxidase. -Antioxidant stress responses: catalase activity, superoxide dismutase (SOD). -Biochemical responses: total protein, albumin, globulin, serum glutamic pyruvic transaminase (SGPT), and serum glutamic oxaloacetic transaminase (SGOT).	- Rohu, bivalve, and floating weed co-cultures can improve water quality, increase fish immunity, and increase productivity and survival rates. -It is necessary to conduct a study on the use of other types of extractive species (plants and shellfish) originating from local areas that are relevant to the cultivation activities; another study is the calculation of nutrient load and sequestration in co-culture cultivation to determine the value of the overall system effectiveness.	(Nath et al., 2021)
The utilisation of three strains from Lemna minor in the bioremediation process in aquaculture waste disposal with a maintenance period of 5 weeks (part 1) and one year (part 2).	-Water quality: water temperature, pH, NO$_2^-$, NO$_3^-$, NH$_4^+$, and PO$_4^{3-}$. -Bioremediation performances: concentration of chlorophyll, and cyanobacteria. -Monitoring of duckweed surface coverage.	*Lemna minor* can maintain water quality under controlled conditions in the IMTA system.	(Paolacci et al., 2022)
IMTA system fish farming integrated with NTF and FRS system hydroponic cultivation.	-Water quality: NH$_3^+$, NO$_2^-$, NO$_3^-$, PO$_4^{3-}$, carbonate, (CO$_3^{2-}$), bi-carbonate, (HCO$_3^-$), TDS, BOD, COD, major cations (Ca, Mg, K, Na) and major anions (F, SO4) Metals (Al, As, Ba, Cd, Cr, Co, Cu, Fe, Mn, Ni, Pb, Se, Sb, Sn, Zn).-Water use efficiency (WUE).-Nutrient use efficiency (NUE).-Biomass production.	- Integrated application of IMTA with hydroponic cultivation can significantly increase production and water and nutrient use efficiency (WUE and NUE) compared to traditional horticultural models and monoculture aquaculture.	(Ibáñez Otazua et al., 2022)

commercial purposes and overcoming pollution. In the IMTA system, the species used are commercial and environmentally friendly (Chopin, 2006; Troell, 2009). Several studies on marine-brackish water IMTA have been carried out and can be seen in Table 4.

The results of several studies show that the IMTA system's application to marine-brackish water improves water quality in the culture media and increases profitability and balance in the system. Further research needs to be done using a combination of potential local extractive species on a larger scale to understand better system performance, the ratio of species used in the systems, and integration between IMTA and other systems.

IMTA integrated BFT and RAS

The current IMTA system has evolved in its application. One development model combines it with other systems, such as the RAS and BFT (Biofloc Technology) systems. The purpose of the combination of these systems is to find a model that is suitable for sustainable and environmentally friendly aquaculture activities. Cultivation with the BFT system generally produces solids (TSS) and nutrients (especially nitrate and phosphate), which

Table 4. Study research on marine-brackish water IMTA.

Treatments	Parameters	Conclusions and recommendations	References
Use oysters in the sea cucumber cultivation for 216 days of the rearing period.	-Growth performances: initial wet, final wet, specific growth rate (SGR of sea cucumber). -Water quality: water temperature, total nitrogen (TN), total organic carbon (TOC), isotopic analysis, stable carbon, and nitrogen isotope ratios (d13C, d15N).	-Co-culture activities on sea cucumber with Pacific oyster showed good growth and high SR (100%) for 216 days of the rearing period. -The need for research on a larger scale to better understand the capabilities of Pacific oysters and sea cucumber cultivation using the IMTA system.	(Yokoyama, 2013)
The use of algae integrated with shrimp in two IMTA systems with a maintenance period of 7-18 days.	-Growth performances: density, weight, and shrimp biomass. -Water quality: water temperature, salinity, oxygen saturation, dissolved oxygen (DO), pH, NO_2^-, NO_3^-, NH_4^+, light insolation, total dissolved inorganic nitrogen flux (TIDN Flux), water turnover rate. -Macroalgae performance: algae stocking density, specific algal growth rate, tissue nitrogen content in dry weight (N in DW), algal tissue, the content ratio of carbon to nitrogen in dry weight (C:N ratio), and nitrogen assimilation rate into algal tissue per square meter.	*Gracilaria tikvahiae* and *Litopenaeus vannamei* grow quickly, and most of the nitrogenous waste is converted into algal biomass, which can be harvested and marketed.	(Samocha et al., 2015)
Co-culture between sea bream and mullet compared to sea bream and mullet monoculture with a rearing period of 284 days.	-Growth performances: fish weight, yield, SGR, FCR, and SR. -Biochemical composition: protein, carbohydrate, lipids of the fish feed and the sludges. -Water quality: water temperature, pH, oxygen saturation.	Co-culture between sea bream and mullet increases biomass, nitrogen assimilation, and dissolved oxygen emissions, reducing FCR, sediment amount, and nitrogen in sediment.	(Shpigel et al., 2016)
Comparison between monoculture shrimp rearing and shrimp-seaweed integration with the biofloc system with a rearing period of 42 days.	-Growth performances: final weight, survival, yield, biomass gain, weight gain, weekly growth, FCR, SGR of shrimp. -Water quality: temperature, salinity, settleable solids (SS), total suspended solids (TSS), pH, DO, TAN, NO_2^-, NO_3^-, PO_4^{3-}, and Alkalinity. -Vibrio monitoring. -Proximate analysis: crude protein, crude lipid, moisture and ash.	Shrimp-seaweed integration in the biofloc system (BFT) can improve water quality, reduce Vibrio density, and increase growth and protein content in shrimp bodies.	(Brito et al., 2016)

Table 4. Continue.

Treatments	Parameters	Conclusions and recommendations	References
The utilisation of red algae for the bioremediation process in cage cultivation was carried out for 35 days.	-Water quality: water temperature, salinity, pH, DO, chemical oxygen demand (COD), NO_2^-, NO_3^-, NH_4^+, and PO_4^{3-}, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphate (DIP), and eutrophication index (E). -Macroalgae performances: growth rate of red algae. -N and P content in yellow croaker, red algae, and feed.	-Utilisation of the optimal proportion of red algae will balance the nutrients produced from fish farming in the IMTA system. -The need for further studies focusing on bioremediation by cultivating macroalgae throughout the year to improve the aquaculture environment.	(Wei et al., 2017)
Use of *Ulva lactuca* with different percentage ratios as feed on sea bream.	-Growth performances: SGR, yield, FCR, protein productive value (PPV), and SR. -Food biochemical composition: proteins, carbohydrates, lipids of ulva, and fish feed.	The utilisation of *Ulva lactuca* as a protein supplement can save feed production costs by 10%, reduce the concentration of nitrogenous waste in the culture media, and save water treatment costs.	(Shpigel et al., 2017)
The use of sea urchins as algivorous in semi-commercial groundfish-seaweed-sea urchin IMTA systems was carried out for 460 days of the rearing period.	-Water quality: water temperature, DO, and pH. -Growth performances: SGR of fish and sea urchins, FCR, gonad somatic index (GSI) of sea urchins.-Roe colour assessment for the sea urchin. -Biochemical composition: protein, carbohydrate, lipids, ash of fish, sea urchins, and ulva. -Nitrogen and biomass budgets.	Using *U. Lactuca* as a biofilter can improve waste treatment and the system's sustainability.	(Shpigel et al., 2018)
The use of a combination of extractive species in rearing three types of fish with different trophic levels in semi-intensive seawater aquaculture in earthen ponds.	-Water quality: water temperature, DO, pH, salinity, turbidity, transparency, NO_2^-, NO_3^-, NH_3^+, PO_4^{3-}, and silica (Si). -Phytoplankton analysis: chlorophyll *a*, phaeopigments, and degradation ratio. -Growth performances: biomass, fish density, FCR, total weight (TW), total length (TL), condition factor (K), specific growth rate (SGR), and daily growth index (DGI) of fish); biomass, density, and FCR for all species. -Fish parasite analysis: prevalence and infestation level of ectoparasites in reared fish.	-Integration of fish, oysters, and macroalgae can improve water quality, increase biomass production, reduce energy use by 14% daily, and generate greater profitability.	(Cunha et al., 2019)
The use of extractive species (organic and inorganic) in utilising waste from rearing European sea bass with the RAS system, as well as the use of algae as feed in oyster production, which is reared for 60 days.	-Water quality: RAS-IMTA systems: water temperature, salinity, pH, DO. -Nutrients: Algae: CO_2 concentrations; Oyster: temperature, salinity, and nutrients (NO_2^-, NO_3^-, NH_4^+, and PO_4^{3-}).	-The application of the RAS-IMTA system can remove nutrients like the microalgae-based IMTA system. -The microalgae-based RAS-IMTA system can produce as much as 20.5–33.3 g Algae gN^{-1} and 0.07–0.09 g Chla gN^{-1}. -Oyster growth is prolonged. -The need for research is to increase oysters' growth by optimising access to food and adding a CO_2 source to stabilise the media's pH value and maintain the microalgae stability.	(Li et al., 2019)

Table 4. Continue.

Treatments	**Parameters**	**Conclusions and recommendations**	**References**
Comparison between monoculture shrimp and mullet with integrated shrimp-mullet models with co-culture and sequential/ different tank models.	-Water quality: water temperature, DO, salinity, pH, alkalinity, TSS, TAN, NO_2^-, NO_3^-, and settleable solids (SS). -Growth performance: Shrimp: final mean weight, SR, SGR, FCR, biomass, and yield; Mullet: weight gain (WG), SGR, biomass, and SR. -Hepatosomatic index (HSI) and condition factor (K) of Mullet, total vibrio count (TVC). and total heterotrophic bacteria.	-Adding a mullet to an integrated system can reduce the population of *Vibrio* spp. in an integrated pond. -Integration between mullet and shrimp can be done in the same tank.	(Borges et al., 2020)
Comparison of shrimp monoculture with integrated shrimp-mullet rearing with co-culture and sequential/ separate models carried out for 31 days of the rearing period.	-Water quality: DO, water temperature, pH, salinity, turbidity, TSS, TAN, NO_2^-, NO_3^-, PO_4^{3-}, and alkalinity. -Growth performance: SR, final mean weight, total biomass, weekly growth gain, apparent feed conversion ratio (AFCR), productivity.	-Mullet can utilise solids derived from shrimp production with the BFT system. -There is a need for further research to find out better mullet and shrimp ratios and feeding rates and studies on a mass scale to determine the economic analysis.	(Holanda et al., 2020)
Fish rearing using the polyculture model was compared to IMTA using a combination of different extractive species with a rearing period of 150 days.	-Water quality: water temperature, pH, salinity, DO, NO_2^-, NO_3^-, NH_3^+, and PO_4^{3-}. -Body composition analysis of harvested fish and shrimp. -Economic performance: total income, net income, and benefit-cost ratio (BCR).	Using mullets and tiger shrimp as fed species and oysters and water spinach as extractive species increased net income by 3.35, 3.48, and 1.6 times in the IMTA system with low-salinity brackish water. Furthermore, the water quality with the IMTA system is better than a conventional polyculture using mullets and shrimp.	(Biswas et al., 2020)
Utilisation of micro-invertebrates and seaweed as extractive species placed around seabass or sea bream production areas using the long-line method.	-Growth performance: Sponge: survival (living, dead or damaged), and SGR; Worm: length and weight measurements; Seaweed: SGR. -The health status of the worm. -Analysis of the consistency and colouring of the algae.	-Utilisation of species diversification can help improve efficiency in screening systems and provide commercial advantages. -Need to pay attention to the rearing time and the harvested biomass of each species reared. -Need for investigations regarding market analysis of using sponges and Polychaeta as species that utilise by-products in the IMTA system.	(Giangrande et al., 2020)
The rearing of fat greenling monoculture integrated with polychaetes as an extractive species using different stocking densities was carried out for 30 days.	-Chemical analysis: Carbon and nitrogen in fish, polychaetes, and sediment.-Growth performances: initial body weight, final body weight, SGR, SR, moisture content, feed consumption. -Nitrogen and carbon budget. -Nitrogen and carbon discharge comparison.	The use of Polychaeta can utilise particulate organic waste from intensive fish farming.	(Hu et al., 2021)
The rearing of vannamei shrimp with monoculture, co-culture with BFT, and shrimp monoculture with BFT was carried out for 30 days.	-Water quality: water temperature, Salinity, pH, DO, NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-}. -Growth performance: shrimp: length gain, average percentage weight gain (AWG), SR; shrimp and seaweed: final biomass, SGR.	Using seaweed integrated with the BFT system has the potential for sustainability and good production. The use of seaweed can improve water quality in intensive shrimp farming in brackish water.	(Sarkar et al., 2021)

Table 4. Continue.

Treatments	Parameters	Conclusions and recommendations	References
Shrimp rearing with monoculture and IMTA systems using two types of organic extractive species was carried out for 135 days.	-Growth Performance: ABW, net weight gain (NWG), DWG, SGR, daily growth rate (DGR), AFCR, survival, and yield.-Water quality: Salinity, pH, DO, water temperature, EC, TDS, TAN, NO_2^-, NO_3^- and PO_4^{3-}.	-Integrated system cultivation shows better results than monoculture cultivation. -Utilisation of extractive species can increase profitability and improve the balance of the system in the cultivation environment. -The need for further research on using different and commercial combinations of extractive species and more extended cultivation periods to assess the suitability of the cultivation and application of the IMTA system.	(Magondu et al., 2022)
The use of oysters with different stocking densities in shrimp rearing using the IMTA-Biofloc system compared to monoculture was used for 45 days.	-Water quality: water temperature, salinity, pH, TDS, TSS, SS, DO, alkalinity, TAN, NO_2^-, NO_3^-, and PO_4^{3-}. -Zootechnical performance: biomass gain, mean final weight, SGR, FCR, SR, and yield. -Proximate composition: crude protein, lipid, ash, and fibre in the floc samples. -Vibrio count -Total haemocyte count for shrimp and oysters.	-Using multitrophic biofloc between shrimp and oysters can reduce nitrogen and solids content in the culture media and reduce vibrio bacteria during the nursery phase. -The high stocking density of oysters (300 oysters m^{-2}) can reduce the water quality in the pond and the nutritional content of the flocs due to the high rate of the filtration process.	(Lima et al., 2021)
The use of a combination of different extractive species in the maintenance of tiger shrimp was carried out for ± 30 days.	-Water quality: water temperature, pH, salinity, DO, TOM, TAN, NO_2^-, and NO_3^-. -Growth performances: SGR and SR.	Integrated farming of tiger shrimp with seaweed and blood cockle can improve water quality by reducing the concentration of TOM, TAN, NO_2^-, and NO_3^- in the rearing medium and increasing the SR level of the shrimp.	(Amalia et al., 2022)

tend to increase at the end of the rearing period (Azhar et al., 2020; Gaona et al., 2011; Khanjani & Sharifinia, 2022; Ray et al., 2010). With the application of the BFT system integrated with IMTA, organic and inorganic extractive species are expected to utilise solids and nutrients to be used as harvestable biomass products and keep the rearing medium in optimal conditions for cultivation.

Several studies on the IMTA-integrated BFT system have been carried out. They show that it can improve water quality in the rearing medium by increasing efficiency in nutrient absorption in the form of inorganic nitrogen (NH_4^+, NO_2^-, NO_3^-) and phosphate (PO_4^{3-}), utilisation of dissolved solids (Borges et al., 2020; Brito et al., 2016; Lima et al., 2021), as well as increasing biomass production with species diversification (Poli et al., 2019). However, the use of proportions of extractive species that are not suitable can also have negative impacts, such as decreasing water quality and the nutrient content of flocs due to the use of high oyster stocking densities so that the filtration rate increases (Lima et al., 2021). However, evaluation of the integrated BFT system still needs to be carried out, especially in commercial applications, and economic analysis of the cultivation application needs to be performed for a longer period of time.

RAS (Recirculating Aquaculture Systems) is a system that is currently being widely used in land aquaculture activities. With the application of the RAS system, it is possible to produce various species by minimising the use of natural resources, especially in utilising water sources (Martins et al., 2010; Orellana et al., 2014). In the RAS system, the level of water consumption for aquaculture activities is reduced without any water changes or maximally with water changes of <1% of the system volume per day (Waller et al., 2015). Bio-process technology using biological and mechanical filters plays a vital role in the RAS system because it functions to maintain water quality to remain stable. However, the accumulation of solids and nitrates resulting from the bio-process significantly affects the system's stability. Based on this, it is necessary to utilise nutrients derived from commercial RAS waste (Orellana et al., 2014).

Future Challenges

The IMTA system is currently developing towards using extractive species that have work potential in the system and have commercial value. In addition, it is also necessary to use technology that can utilise natural energy to be more efficient in energy use. The challenge will be faced by focusing on three aspects: 1) economic elements in the form of investment capital, methods of maintenance and harvesting, and system design for mass scale; 2) from the biological aspect, the effects of weather changes on water quality, limitations on the use of suitable species, residues, and contamination from using chemicals in aquaculture; and 3) from the social aspect, concerns from the community about the impact on the environment, competition in the utilisation of natural resources, and conflicts between stakeholders (Buck et al., 2018; Oyinlola et al., 2018; Rosa et al., 2020; Sasikumar & Viji, 2015; Troell et al., 2017b). Selection of appropriate species and managing the flow of nutrients are essential in increasing production and producing optimal models adapted to cultivation conditions (Granada et al., 2016; Rosa et al., 2020; Sasikumar & Viji, 2015). Currently, the cultivation of the IMTA system is still in the development stage in many countries. This has positive and negative impacts on several sides. Increasing land use and food security must also be considered because IMTA is a complex system. Therefore, it is necessary to enact special laws focusing on socio-economic aspects such as area utilisation and biological elements in residues and contaminants resulting from cultivation activities (Rosa et al., 2020; Sasikumar & Viji, 2015).

CONCLUSION

The concept of eco-friendly aquaculture is the key to sustainable aquaculture in the future. The IMTA system is one of the solutions that can overcome the waste generated from intensive aquaculture activities. Approaches from the environmental side have been carried out through various studies and have shown positive results in improving the ecological conditions of cultivation. However, IMTA studies through economic and social approaches still need to be performed. If more IMTA studies using economic and social approaches are carried out, we suspect that the IMTA system will become popular and widely applied to aquaculture activities.

Acknowledgement: This work was supported by the Scientific Research Projects Coordination Unit of Istanbul University. Project numbers: FDK-2022-39219.

Conflict of interest: The authors declared that they have no conflict of interest.

Ethics Committee approval: Ethics committee approval is not required.

Financial Disclosure: -

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