Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-022-22371-8

REVIEW ARTICLE

Integrated multitrophic aquaculture (IMTA) as an environmentally friendly system for sustainable aquaculture: functionality, species, and application of biofloc technology (BFT)

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Received: 17 February 2022 / Accepted: 29 July 2022

Abstract
Aquaculture is one of the fastest-growing industries in the world, and its prominent role has been proven in supplying food for the growing world population. The expected growth of aquaculture requires the development of responsible and sustainable approaches, technologies, culture systems, and practices. The integrated multitrophic aquaculture (IMTA) system has been developed over the past decades. This system is based on the use of all food levels for simultaneous production of some aquaculturally species in a way that contributes to environmental sustainability (biocontrol), economic stability (product diversity and risk reduction), and social acceptance (better management operations). In IMTA, selecting suitable culture species and considering their appropriate population size is absolutely necessary to achieve an optimal biological and chemical process, improving the ecosystem health and sustainability of the industry. Biofloc technology (BFT) is closely related to the IMTA system, where the IMTA potential can be used to control suspended solids in aquaculture systems with limited water exchange. This study reviews the significance of IMTA systems, potential target species for cultivation, the relationship between BFT and IMTA, total suspended solids control, the economics of IMTA farming, and the recent findings in these fields.

Keywords Environment · Aquaculture sustainability · Integrated multitrophic aquaculture · Biofloc technology · Total suspended solids

Introduction

Aquaculture has rapidly grown recently, referred to as the "blue revolution." Despite the recent episode of its rapid growth, the future of this industry will face challenges such as maintaining its long-term sustainability (FAO 2020; Thomas et al. 2021; Khanjani et al. 2022a), the detrimental impact of monoculture systems on the environment, and, more importantly, overcoming existing constraints on water supply, fish meal, and land (Rodrigues et al. 2019; Boyd et al. 2020).

Eutrophication results from the release of nutrients into the aquatic ecosystem and affects different parts of the ecosystem (Perdikaris et al. 2016; Tórz et al. 2022). Reports indicate that 80–88% of the carbon (C), 52–95% of the nitrogen (N), 85% of the phosphorus (P), and 60% of the aquafeed which enters aquaculture systems leaves it in the particulate, dissolved, or gaseous forms (Estim 2015; Tom et al. 2021) which provides the nutrients needed for the growth of phytoplankton and bacteria. Feces and uneaten feed make up the particulate organic matter (POM) waste fraction (Wang et al. 2012), and 5–45% N, 42–57% P, and 6–44% C in the feed are released as POM in the environment (Reid et al. 2009; Bureau and Hua 2010). Particulate and dissolved forms can also carry heavy metals and drug residues that are hazardous to aquatic animals (Sharifinia et al. 2022).

Responsible Editor: Philippe Garrigues

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Published online: 03 August 2022

Recently, the development of an environmentally friendly aquaculture system and particular treatment facility has been investigated to remove pollutants/excess nutrients that cause eutrophication (Perdikaris et al. 2016; Thomas et al. 2021). For example, the use of biofilter organisms from the different trophic levels in the aquaculture system to remove the animal waste products in the water is known as an IMTA system (Chopin et al. 2000).

The IMTA has been developed to improve sustainability in intensive aquaculture by employing an ecosystem-oriented approach, combining fed aquaculture species (e.g., finfish or shrimp) with organic extractive aquaculture species (e.g., shellfish or herbivorous fish) and inorganic extractive aquaculture species (e.g., seaweed) to create a balanced system to promote environmental sustainability (biomitigation), economic stability (product diversification and risk reduction), and social acceptability (better management practices) (Neori et al. 2004; Troell et al. 2009; Biswas et al. 2020; Sanz-Lazaro and Sanchez-Jerez 2020). The IMTA promises to increase the yield of low-trophic species by using surplus feed from high-trophic animal cultures. Furthermore, it reduces the negative environmental impact of culture operations by removing organic matter from wastewater (Soto 2009).

Our review covers previous findings concerning the IMTA system with a specific emphasis on the functionalities of this system, its suitable species, application of biofloc technology (BFT), controlling of the total suspended solids (TSS), its economy, and future challenges as well as on the ongoing discussion of the prospects of the offshore and land-based IMTA system.

Functionalities of the IMTA system

Over the last 20 years, we have seen the growth of integrated aquaculture as a method of nutrient mitigation in intensive aquaculture, especially in marine environments. One of the best examples in this regard is IMTA. Some recent studies in this area are presented in Table 1. The IMTA takes advantage of the simultaneous cultivation of multiple species, including fish, oysters, seaweeds, sea cucumbers, sea urchins, or even more specialized species, including halophytes such as mangroves (Soto 2009). In the IMTA system, the unutilized food, mineral excrement, and metabolites produced by organisms from one trophic level are used to cultivate plants, mollusks, echinoderms, etc. with the following goals: (i) restoring balance to the environment, improving environmental conditions and bioremediation, and (ii) enhancing economic durability (improving the product, cutting costs, product diversification, cost reduction, and more net benefit), (iii) increasing social acceptance of aquaculture products (through publicizing better management practices) (Chopin et al. 2001; Neori et al. 2004; Barrington et al. 2009; Cutajar et al. 2022).

In IMTA, selecting the appropriate combination of species and population sizes is crucial to achieving a sustainable balance and contributing to ecosystem health (Chopin 2006). This cultivation method also contributes to environmental protection and increases total yield (Sanz-Lazaro and Sanchez-Jerez 2020; Rosa et al. 2020). Some advantages of IMTA include the following:

- Effluent bio-mitigation: effluent management through the application of biofilters that fit the operation's ecology and ecological niche. This solution can overcome some of the issues arising from monoculture (Granada et al. 2018; Correia et al. 2020).
- Increased profits through diversification: the improved total economic value of an aquaculture operation through the sale of commercial by-products. These economic gains also help offset the costs of complex bio-filtration setups (Ridler et al. 2007; Fonseca et al. 2015).
- Contributing to the local economy: promoting economic growth through direct and indirect employment (Fonseca et al. 2015; Knowler et al. 2020).
- Natural crop insurance: the diversity of products provides a safeguard against price fluctuations for any single product, as well as protection against loss of crop due to disease or harsh weather (Sasikumar and Viji 2016; O'Neill et al. 2022).
- Disease control: some seaweed species exhibit antibacterial activity which can prevent or control diseases among farmed fish (Chopin 2013; Granada et al. 2016).
- Increased profits by charging premium prices: IMTA products can sell for higher prices through eco-labeling schemes or organic certification programs (Carras et al. 2019).
- Reduction or elimination of dependence on fish meal and fish oil (Granada et al. 2016).

On the other hand, there are some disadvantages for IMTA including the following:

- The artificial installed system is prone to disease outbreaks. The culture species are confined to a non-natural environment, and thus, they are more susceptible to infection from each other and from outside sources (Stabili et al. 2010; Granada et al. 2016).
- Here, the probability of system collapse is high because it relies on inputs of several trophic levels (plants, fish, and invertebrates) to succeed. If any of these levels are affected, the whole system may collapse (Chopin 2017).
- The IMTA regulation has not yet been available to strongly control the system. In practice, this can be dif-

Table 1 The previous study about utilization of the IMTA systems in aquaculture

Study done	Period study (days)	IMTA system placement	Results and conclusions	References
Integrated culture of shellfish (*Haliotis discus* hannai), sea cucumber (*Apostichopus japonicas*) and fish (*Sebastes schlegeli*) in a recirculated aquaculture system	60	Tank culture	Combination of shellfish and sea cucumber improved nutrient-use rate (N and P) and also, shellfish growth	Gao et al. (2019)
The rearing of the two bioremediators, *Sabella spallanzanii* and the macroalga *Chaetomorpha linum*, in an integrated rearing fish system was realized, in the Mediterranean Sea	60	Coastal	The high biomass of *Sabella spallanzanii* and macroalgae (*Chaetomorpha linum*) can be used in the diet of European seabass fish	Stabili et al. (2019)
Investigation of algal growth- and morphogenesis-promoting factors in a IMTA system with *Ulva* sp. and farmed fish (seabream and seabass)	360	Land-based, pond culture	Sustainable growth and development of *Ulva* sp. can benefit from naturally enriched AGMPFs and their in situ production by bacteria	Ghaderiardakani et al. (2019) and Califano et al. (2020)
Polyculture of an iliophagus fish (*Prochilodus lineatus*) with the integrated culture of pelagic fish (*Colossoma macropomum*) and benthic prawns (*Macrobrachium amazonicum*)	53	Pond culture	Wastes converted to biomass by nutrient cycling increase. Also, augmentation of final biomass, and about 1/3 decrease in FCR	Franchini et al. (2020)
Combination of red seaweed *Solieria filiformis* with sea cucumbers and fish in a IMTA system	70	Tank culture	Various growth rate and biochemical composition of red algae in the designed system was observed which was depending on what organism grows next to it. *S. filiformis* is proposed as an appropriate species to be integrated with fish and sea cucumbers in tropical environments	Felaco et al. (2020)
Food web structure and ecosystem characteristics of IMTAS in Sanggou Bay	360	Sanggou Bay, coastal	Biomitigation, ecosystem protection and economic benefits	Sun et al. (2020)
Comprision of an IMTA system consist of fed and extractive species with traditional polyculture in low saline brackish water pond system	150	Land-based, earthen ponds (500 m^2)	IMTA involving mullets and tiger shrimp as fed species, and oyster and water spinach as extractive species resulted in 3.35-, 3.48-, and 1.6-fold increase in total production in low saline brackishwater. The introduced IMTA model proved to be productive, and economically viable with environmental bio-remediation effect	Biswas et al. (2020)
Integrated culture of deposit-feeding *Hediste diversicolor* and finfish, and subsequent biomitigation	98	Tank culture	*H. diversicolor* has cumulated assimilation rates, and it represents 75–289 kg of fish waste/year for a 100 m^2 ragworm farm (3700 ind. m^{-2})	Galasso et al. (2020)
Combination of freshwater bivalves and rainbow trout, for the bioremediation purposes in inland culture systems	42	Inland aquaculture systems, tank culture	The used bivalves was effective in reducing of *A. hydrophila* load. It proposed as a biotechnological tool against the antibiotic resistance	Sicuro et al. (2020)

Table 1 (continued)

Study done	Period study (days)	IMTA system placement	Results and conclusions	References
Unravelling the fatty acid profiles of different polychaete species cultured under integrated multi-trophic aquaculture (IMTA)	105	Tank culture	The polychaetes biomass with high nutritional value could be produced by systems like IMTA. Such systems support a cleaner production of these animals, and more importantly, they make possible recovery of essential fatty acids which are traditionally wasted in effluents of aquaculture facilities	Jerónimo et al. (2020)
The effects of different feed limitation of C:N ratios on growth parameters, survival, body composition and amino acid profile of *Macrobrachium borellii* in an IMTA system	67	Tank culture (60 cm diameter × 50 cm high, filled with 80 L of tap water)	Combining *Macrobrachium borellii* with omnivore or carnivore fish species can yield satisfactory results. The amino acid profile was rich in lysine, leucine, and arginine. *M. borelliii* was proposed as a considerable by-product which can be used by human and animal	Carvalho et al. (2020)
Red drum (*Sciaenops ocellatus*) and sea cucumber (*Holothuria scabra*) in an IMTA system: both bioremediation and life-cycle impacts was eximend	360	Coastal culture	The appropriate biomass ratio of sea cucumber to finfish should be 1.3/1 kg. this ratio is required for 100% removing of finfish feces particulate waste. *H. scabra* at the high densities has a good potential for bioremediation	Chary et al. (2020)
The comparison of antioxidant activity of wild-collected and IMTA cultured marine macroalgae	28	Tank culture	The IMTA conditions affect the biochemical composition of algae	Vega et al. (2020)
Combination of mussel (*Perna perna)* and cobia (*Rachycentron canadum)* in a designed IMTA system	10 years	Coastal, area of 2000 m^2, net cages	The system was more resilient, profitable, and diversified. The time of ecomominc return is more reasonable with lower risks compared to the monoculture systems	Bergamo et al. (2021)
Inclusion of the red alga *Gracilariopsis tenuifrons* (biofilter) in a IMTA system with *Litopenaeus vannamei*, using recirculation by zero water exchange	28	Tank culture, using recirculation by zero water exchange	Inclusion of *L. vannamei* with G. *tenuifrons* as a biofilter can be supportive and lessen water usage and eliminate the main metabolites produced by shrimp cultivation	Carneiro et al. (2021)
Integrated culture of a Indian major carp, *Labeo rohita* with *W. globosa* (as inorganic extractive species) and *L. marginallis* (as organic extractive species)	90	Outdoor cement tanks (20 m^3 each)	Addition of *W. globosa* for water remediation generates economic returns and environmentally viable aquatic food production. Water quality improvement protects fish from oxidative stress, and improved the fish immunity and survival	Nath et al. (2021)

Table 1 (continued)

Study done	Period study (days)	IMTA system placement	Results and conclusions	References
Evaluate the nutrient (N and C) balances in IMTA mode of *Hexagrammos otakii* and *Perinereis aibuhitensis*	30	Pond culture	The used fish-polychaete system could decrease the carbon and nitrogen discharge Reduction of flow velocity by enlarging the pond length would help the remediation effect of polychaetes. *P. aibuhitensis* is promising in the environmental recovery of sediment in IMTA	Hu et al. (2021)
Survey of IMTA system execution in the commercial levels at the landscape scale in southern Chile	10 years	Coastal zone, bays, and channels	The possibility of IMTA in commercial farms was confirmed. The usefulness and implication of the present rules was discussed in Chile. Finally, the implementation changes was proposed within the ecological framework to aquaculture	Camelo-Guarín et al. (2021)
Ulva fasciata was added at different levels to two diets for *Seriola dorsalis*: isoproteic and isolipidic ones (45% crude protein and 12.5% crude fat). The effects of supplemented diets was studied on growth performance, hematology, and fatty acid profile in muscle	48	Circular tanks with 500 L of water volume connected to a recirculating aquaculture system	No significant growth changes was observed by the IMTA-cultivated *U. fasciata* supplemented diets in *Seriola dorsalis* after 48 days. Nonetheless, the muscle tissue of fish fed *U. fasciata* at 10 g kg^{-1} was enough to reveal differences in increase hematocrit and DHA accumulation	Legarda et al. (2021b)
The efficiency of *Sarcocornia neei* during nutrient removing in the both marine fish farms wastewater and artificial effluents simulating different nitrogen loads	70	Sand-substrate systems, 30 m^2 greenhouse	As a promising biofilter, *Sarcocornia neei* is an appropriate species for bioremediation purposes. Numerous advantages was declared. The most important of which are increase of growth and productivity rates; the ammonia, phosphate, and nitrate removal efficiencies; the accumulation of organic C, N, and P compounds; and adaptability to high salt concentrations	Beyer et al. (2021)
Investigated trophic fractionation of fish-derived waste materials by co-cultured species in an IMTA practice off Tongyoung Coast	2 years	Tongyoung Coast, square floating cages (12 m × 12 m)	Firstly, *Apostichopus japonicus* is more effectual to reduce wastes load among the extractive species. Secondly, *Crassostrea gigas* is an important co-cultured species to reduce the aquaculture wastes followed by *Mytilus galloprovincialis*. Finally, seaweeds are least responsible to reduce the biodeposit loads. Accordingly, *Apostichopus japonicus*, *Crassostrea gigas*, and *Mytilus galloprovincialis* might be more suitable to reduce the adverse impact of aquaculture wastes on coastal environment	Park et al. (2021)

Table 1 (continued)

Study done	Period study (days)	IMTA system placement	Results and conclusions	References
The potentials of macroalgae *Agardhiella subulata* for use in IMTA systems in South Florida	30	Tank culture	Suitability of the tested macroalgae was confirmed for IMTA systems where it shows the good growth and efficient nutrient removal. For this purpose, it considered a promising species in the designed IMTA systems in the Atlantic, Gulf of Mexico, and Caribbean regions	Lohroff et al. (2021)
Evaluate the productivity, nutritional profile, and nutrient extraction capacity of *Halimione portulacoides* (L.) Aellen, a common edible halophyte of European saltmarshes, in saline hydroponic conditions to understand its horticultural potential for IMTA in brackish waters	70	Coastal lagoon	*H. portulacoides*, a suitable extractive species for coastal IMTA, can be highly productive in hydroponics using saline water irrigation with non-limiting concentrations of dissolved inorganic nitrogen and phosphorus	Custódio et al. (2021)
Sea cucumber *Holothuria scabra*, cockles *Anadara antiquata*, and Indian wild shrimp *Penaeus indicus* were cultured simultaneously in an IMTA system in Kenya. The obtained results were compared with monoculture systems for shrimp in intertidal earthen ponds	135	Earthen pond culture	Inclusion of *H. scabra* and *A. antiquata* into Kenya's coastal mariculture through IMTA approach could yield appropriate results	Magondu et al. (2021)
Investigation of quantitative and qualitative transformations of nitrogen compounds in the IMTA system using the media filled beds (MFB) method in plant cultivation	147	Tank culture ($1m^3$)	During the course of the study, the nitrification process was observed. Initiation of the anammox and denitrification processes was observed. These processes may have been triggered using the MFB method in plant cultivation	Tórz et al. (2021)
The lagoon presence was examined on a freshwater fishpond performances in an IMTA	281	Pond culture	The use of a lagoon shows environmentally friendly practices	Jaeger et al. (2021)
The effects of *Lemna minor* on effluent remediation in IMTA using newly developed synthetic aquaculture wastewate	4	Plastic container culture	Potential nutrient uptake by Lemna minor was calculated. Such investigations can help to modern design of phytoremediation systems	Paolacci et al. (2021)
IMTA-produced macroalgae, *Saccharina latissima*, was examined for the total phenolic compounds and antioxidative capacity	240	Coastal culture	The obtained results confirmed that *S. latissima* and its culture method have pivotal role for the development of natural food additives, functional food, or safe products from seaweed	Mildenberger et al. (2022)

AGMPFs the activity of algal growth- and morphogenesis-promoting factors, *FCR feed conversion ratio* ficult to manage, leading to inefficient production and reduced sustainability (Buck et al. 2018).

- This system is dependent on external inputs such as fish feed and water. When these resources become rare or expensive, production can quickly derail (Wilfart et al. 2020).
- The IMTA system can lead to overpopulation and overcrowding of organisms cultured. Overpopulation also leads to increased animal stress levels, and triggers the rapid spread of disease and high mortality (Granada et al. 2016; Chopin 2017).

Organic and inorganic extractive species (e.g., shellfish and seaweed, respectively) play an essential role in IMTA operations since extractive species are capable of reducing the waste produced by fed species by retaining and using suspended organic matter (Alexander and Hughes 2017; Barrington et al. 2009; Chopin 2006; Edwards 2015; Kleitou et al. 2018; Martínez-Espineira et al. 2015; Van Rijn 2013; Rosa et al. 2020). IMTA draws upon ecological engineering and requires a deep understanding of ecological processes and species functions in the ecosystem (Troell et al. 2009; Ren et al. 2012; Granada et al. 2016).

According to Barrington et al. (2009), the development of an offshore IMTA system requires a few steps, including explaining the economic and environmental value of the IMTA operation and its products, selection of suitable species, appropriate deployable technologies (compatible with the selected environmental and oceanographic conditions), adoption of the appropriate legislation and regulations, finding new markets, promotion and education, creation of the production chain, and research.

For the successful formation of the IMTA system, all the steps mentioned above must be put together. There also should be a collaboration among biologists, natural and social scientists, aquaculture engineers, economists, and industry investors, and this collaboration is precious. Having an interdisciplinary mindset is essential for the successful formation of IMTA (Chopin 2006, 2018). Also, aquaculture management revision is essential in the integrated coastal area management (ICAM) approach. This approach should be established for further IMTA development, which means that all bays/coastal areas should be an IMTA management unit, not just the relatively small range of breeding sites. One of the main problems of IMTA development is the regulations and laws related to the coastal zone, which has its own laws in different countries. Because the IMTA concept is very flexible, it can be used worldwide for open and land-based systems, marine (offshore and inshore) and freshwater environments, and temperate and tropical climates. Also, different climatic, environmental, biological, physical, chemical, economic, historical, social, political, and governmental conditions lead to different choices in the design and development of IMTA systems (Chopin 2018; Knowler et al. 2020; Reid et al. 2020).

Suitable species for IMTA

The integrated nature of IMTA systems demands a careful selection of species (Zhang et al. 2019; Rosa et al. 2020). The fed component usually consists of carnivorous fish or shrimp, feeding with either pellets or rough fish. Other biological components in an IMTA operation such as bivalves and seaweeds are sustained by the food provided by the environment (Barrington et al. 2009; Strand et al. 2019).

Different species have been explored in the literature, including shellfish/shrimp, fish/seaweed/shellfish, fish/shrimp, and seaweed/shrimp (Troell et al. 2003; Zhang et al. 2019; Table 2). Several factors determine the selection of species:

- The selected species should complement each other from a trophic perspective; that is, species in the lower trophic levels (low-trophic animals) should be able to utilize the waste produced by species in the higher trophic levels (high-trophic animals). Such arrangements reduce water pollution and increase the production of cultivated aquatic species (Barrington et al. 2009; Viji 2015).
- The species should ideally be selected from local species that are well adapted to the environment. The key point of species requirement in the IMTA is having a high growth rate (Largo et al. 2016).
- The site for constructing an IMTA system should be carefully selected since environmental conditions cannot be controlled. Therefore, a comprehensive understanding of environmental conditions is necessary, including organic matter, dissolved inorganic matter, and particle size (Sasikumar and Viji 2016; Chopin 2017).
- Selected species should be able to reach significant biomass (Chopin et al. 2010).
- There should have a market demand for the cultivated species in raw or processed form, or their derivatives should have market value (Shi et al. 2013; Carras et al. 2019).

Finfish

Culturing high-trophic finfish is one of the primary targets of the IMTA systems (Ghosh et al. 2016; Hoang et al. 2018). However, selecting suitable finfish species for use in the IMTA systems depends on two main factors: local diet and market value. Thus, local high-value species should be prioritized (Zhang et al. 2019; Holanda et al. 2020).

To date, several species have been tested for use in the IMTA systems as low-trophic level species, such as mullet (*Mugil liza*). It consumes vegetal matter extracted from effluent and sand, giving it the added benefit of being able to recycle energy from waste products of aquaculture systems

Table 2 The different species used in IMTAs are listed (Adapted from Zhang et al. 2019; Stabili et al. 2019; Giangrande et al. 2022; Califano et al. 2020; Gokalp et al. 2021; Varamogianni-Mamatsi et al. 2022)

Finfish	Crustaceans	Sea weed	Suspension feeder	Deposit feeder	Others
Anoplopoma fimbria	*Penaeus monodon*	*Laminaria japonica*	*Scapharca broughtonii*	*Parastichopus californicus*	*Paracentrotus lividus*
Oncorhynchus tshawytscha	*P. merguiensis*	*Alaria esculenta*	*Patinopecten yessoensis*	*Holothuria pervicax*	*Hediste diversicolor*
O. mykiss	*P. indicus*	*Macrocystis pyrifera*	*Perna canaliculus*	*Apostichopus japonicus*	*Caprella equilibra*
Pagrus major	*P. vannamei*	*Porphyra umbilicalis*	*Argopecten irradians*	*Australostichopus mollis*	*Caprella scaura*
Salmo salar	*P. stylirostris*	*Saccharina latissima*	*Chlamys farreri*	*Cucumaria frondosa*	*Sabella spallanzanii*
Seriola quinqueradiata	*Metapenaeus ensis*	*Ulva lactuca*	*Crassostrea gigas*	*Strongylocentrotus droebachiensis*	*Perinereis aibuhitensis*
Sparus aurata	*Fenneropenaeus chinensis*	*U. ohnoi*	*C. virginica*		
Thunnus orientalis	*Pandalus platyceros*	*U. rigida*	*Mytilus edulis*		
Mugil cephalus		*Gracilaria chilensis*	*M. trossulus*		
M. liza		*G. birdiae*	*Tapes* sp.		
Sebastes schlegeli		*G. lemaneiformis*	*Agelas oroides*		
Gadus sp.		*Chaetomorpha linum*	*Aplysina aerophoba*		
Dicentrarchus labrax			*Axinella cannabina*		
			Hymeniacidon perlevis		

into animal biomass (Shpigel et al. 2016; Holanda et al. 2020). Also, two mullet species (*Mugil cephalus* and *Liza parsia*) and tiger shrimp (*Penaeus monodon*) as the fed species were cultured alongside estuarine oyster (*Crassostrea cuttackensis*) and *enteromorpha* seaweed species as the extractive species (Biswas et al. 2020). Jaeger and Aubin (2018) designed a simultaneous intensive-extensive area system in an IMTA framework using a combination of common carp (*Cyprinus carpio*), roach (*Rutilus rutilus*), and tench (*Tinca tinca*) as the intensive element and a lagoon planted with macrophytes for thatation as the extensive element. The results indicated that nitrogen and phosphorus accumulated in the sediment of the lagoon. Nevertheless, the development and proliferation of phytoplankton were limited in the lagoon, and fish growth parameters decreased in comparison with semi-intensive ponds. Further studies are needed to investigate the possibility of including new low-trophic level fish in this system.

Crustaceans

Crustaceans are considered among the main fed species in the IMTA (Chopin 2015; Zhang et al. 2019; Rosa et al. 2020). However, farming crustaceans come with environmental challenges, including habitat degradation, threatening the integrity of the ecosystem, and competition with natural populations (Paez-Osuna 2001; Nederlof et al. 2022). Shrimps, prawns, crabs, and lobsters are the major crustaceans farmed in the IMTA (Chang et al. 2020). Integrated cultivation of crustaceans has a long history; for instance, Vietnamese rice farmers have also farmed species like *Penaeus merguiensis*, *P. indicus*, *P. monodon*, or *Metapenaeus ensis* in rice paddies (Rosa et al. 2020). Similarly, in Indonesia and other Southeast Asian countries, species such as *P. vannamei*, *P. stylirostris*, *P. monodon*, or crabs such as *Scylla* species have been farmed together and species such as *Panulirus* sp., *Homarus americanus*, and *H. gammarus* (Rosa et al. 2020; Chang et al. 2020). Guerra-García et al. (2016) studied the inclusion of caprellid amphipods (*Caprella equilibra* and *C. scaura*) in the IMTA cultivation and found unsaturated fatty acid content of the detritus (composed of feces and uneaten fishfeed pellets, was obtained of aquaculture tanks used for culture of Meagre (*Argyrosomus regius*)) in the system can sustain adult amphipods.

Mussels

Filter feeders are capable of extracting organic particulate matter from the water column. Mussels are among the species with great prospects for use as filter feeders since they provide economic value and reduce the environmental impact of cultivation (Granada et al. 2016). Mussels such as *Mytilus edulis*, *Mytilus trossulus*, *Patinopecten yessoensis*, and *Crassostrea gigas* are promising candidates for use as extractive species in IMTAs (Sarà et al. 2009; Ren et al. 2012; Chopin et al. 2012; Hargrave et al. 2022).

Several researches have shown that bivalves can be potential biocontrollers for fish farm effluents (specially POM) and other eutrophication sources (MacDonald et al. 2011; Handa et al. 2012; Lander et al. 2013; Granada et al. 2016).

Saccostrea commercialis (oistreoidea) is shown to reduce the suspended solids load and nitrogenous and phosphorous compounds in water (MacDonald et al. 2011).

The high filtering potential of bivalves has been proven in culture systems when they can extract up to 23% OM, and 88% suspended solid waste which was up to 33% organic N; it reduced the chl-a up to 96% and 88% bacteria in the system (Nederlof et al. 2022). In a system where fish, microalgae, and bivalve coexisted, the bivalves consumed the entire microalgae in the water column. On the other hand, fish culture produces total ammonia nitrogen (TAN) and phosphate that microalgae can absorb as 67% and 47%, respectively (Hussenot et al. 1998; Nederlof et al. 2022). In fact, bivalves reserved 58% of TAN-N and 41% of PO_4–P excreted by the fish (only with an assimilation efficiency of 87%) (Fang et al. 2017; Nederlof et al. 2022).

An integrated system using bivalves (*Crassostrea madrasensis*) and finfish (*Etroplus suratensis*) with a recommended ratio a 2:1 fish to oyster, a tropical setting, succeeded at significantly controlling eutrophication (Viji et al. 2014, 2015).

In a study conducted by Largo et al. (2016), the establishment of an IMTA system in the tropical open waters of southern Cebu, the Philippines, uses a combination of locally available species, namely donkey's ear abalone (*Haliotis asinina*) as fed species and seaweeds (*Gracilaria heteroclada* and *Eucheuma denticulatum*) as inorganic extractive species. This study exemplifies the successful utilization of high-value endemic species (i.e., *Gracilaria heterocladaI* and donkey's ear abalone). Generally, shellfish is considered a tank for some finfish pathogens; thus, the insertion of shellfish as filter feeder in the IMTA could alter the infection dynamics for fish pathogens and subsequently reduce the risk of diseases (Pietrak et al. 2012; Granada et al. 2016).

Sea cucumbers

Some of the solid waste produced by the fed species in an IMTA system settles to the bottom in the form of deposits. Consequently, deposit extractive species and detritivores can be integrated into an IMTA system. Studies show that sea cucumbers (holothurians) are potential candidates to fulfill this role (Cutajar et al. 2022). The combination of bivalves (filter feeders) and sea cucumbers (detritus feeders) increases the waste removal efficiency of the system. It is stated that holothurians can consume up to 70% of the deposited organic matter (Granada et al. 2016), thus extracting significant amounts of organic carbon and nitrogen from aquaculture waste (Cubillo et al. 2016). Grosso et al. (2021) studied the co-cultivation of sea urchin (*Paracentrotus lividus*) as the primary species and sea cucumber (*Holothuria tubulosa*) as the extractive species. The results indicated acceptable survival and growth for both species and the feasibility of cultivation using this combination in a land-based system. The utilization of orange-footed sea cucumber, *Cucumaria frondosa*, revealed its high absorption efficiency (> 80%) when challenged with particulate material of higher organic level, such as salmon food and feces (Nelson et al. 2012), and this makes it a good option as an effective organic extractive species for use in the IMTA. Slater and Carton (2009) showed that *A. mollis* grazing significantly reduced the accumulation of both organic carbon and phytopigments associated with deposition from mussel farms. Thus, sea cucumbers may potentially constrain or, in some cases, even reverse the polluting impacts of coastal bivalve aquaculture (Slater and Carton 2009). It has been certified that deposit feeders help sediment OM decomposition by bioturbation and improve OM bioremediations (MacTavish et al. 2012). The assimilation efficiencies of sea cucumbers in integrated systems are highly inconstant (14 to 88%) (Nederlof et al. 2022). The ability of sea cucumbers for extraction is variable) 0.1–20% OM, 3–10% organic C, 7–16% organic N, and 21–25% organic P(from the aquaculture waste fed directly or from sediments enriched with aquaculture waste (Yokoyama 2013; Nederlof et al. 2022).

Polychaetes

Annelid polychaetes can also fill the role of deposit feeders in an IMTA system since they are valued as ornamental species (Granada et al. 2016; Jerónimo et al. 2020; Nederlof et al. 2020) and food for other species, particularly the fed species in the IMTA systems (Brown et al. 2011). Annelids can perform biofiltration, aerate the sediment, positively impact biogeochemical reactions, and contribute to waste control (Brown et al. 2011; Granada et al. 2016; Galasso et al. 2020; Nederlof et al. 2020). Recent studies report bioactive properties for annelid mucus and potential applications in biotechnology (Granada et al. 2016; Rosa et al. 2020). There are ample research opportunities for the applications of polychaetes in integrated aquaculture systems.

The Mediterranean polychaete *Sabella spallanzanii* showed the ability to filter, accumulate, and remove from bacterial waste groups, including human potential pathogens and *vibrios* (Stabili et al. 2010). It can also be used as a portion of suitable food for *D. labrax* juveniles (Stabili et al. 2019). Bischoff et al. (2009) cultured *Nereis diversicolor* in settlement tanks receiving wastewater from a sea bream recirculation system. In addition, Palmer (2010) also evaluated the ability of two intertidal polychaetes, *Perinereis helleri* and *Perinereis nuntia*, reared in sand beds to remediate wastewater from a prawn farm and produce harvestable polychaetes biomass without supplemental feeding using "polychaete-assisted sand filters." Brown et al. (2011) evaluated the costs and potential benefits of waste treatment/mitigation and economic return from using *Nereis virens* as a part of an integrated aquaculture system. The water flow influences the biofiltering efficiency of these polychaetes. The TSS levels and density are the factors that also influence their survival and growth performance (Palmer 2010; Granada et al. 2016; Jerónimo et al. 2020; Nederlof et al. 2020).

Seaweeds

In natural ecosystems, seaweeds act as primary producers and convert inorganic compounds into biomass, which is then consumed by organisms in higher trophic levels (Leston et al. 2011; Torres et al. 2008; Nederlof et al. 2022). They are particularly effective at dissolved inorganic nutrient removal and accumulation of their significant biomasses (Neori et al. 2004; Chopin 2006; Barrington et al. 2009; Leston et al. 2011; Alsufyani et al. 2017; Kang et al. 2021; Nederlof et al. 2022). Therefore, they are used as inorganic extractive species in the IMTA systems, which absorb the nutrients entering the water column and, thus, reduce eutrophication (Chopin 2006; Barrington et al. 2009; Nederlof et al. 2022), and subsequently contribute to bioremediation (Chopin et al. 2001; Neori et al. 2004; Sanderson et al. 2008; Zhou et al. 2006; Samocha et al. 2015). Other than that, seaweeds are currently used as a source of food for humans and animals and a source of medicine (Abreu et al. 2014). Califano et al. (2020) investigated the impact of IMTA cultivation on the microbiome associated with *Ulva rigida* (Chlorophyta) and reported that IMTA cultivation significantly affected the microbial community's structure and make-up, releasing algal growth and morphogenesis-promoting factors (Ghaderiardakani et al. 2019). The authors also discovered previously undetected taxa associated with *U. rigida,* which could have unknown functional traits. Overall aquacultural seaweeds shape the microbiome, which can benefit all trophic levels in the IMTA (Wichard 2022).

Much research is being done using *Gracilaria bursa-pastoris*, *Gracilaria gracilis*, *Chondrus crispus*, *Palmaria palmata*, *Porphyra dioica*, *Asparagopsis armata*, *Gracilariopsis longissima* (Rhodophyta), *Ulva rotundata*, and *Ulva intestinalis* (Chlorophyta) as biofilters for use in the IMTA system (Granada et al. 2016; Nederlof et al. 2022).

The red algae *Gracilaria* spp. and the green algae *Ulva* spp. are effective biofilters. *Gracilaria* spp. have been assessed for their usefulness by indoor (using tank) (Marinho-Soriano et al. 2011; Skriptsova and Miroshnikova 2011), outdoor (using pond) (Abreu et al. 2011), and field (Yang et al. 2006; Abreu et al. 2009). In a study conducted by Marinho-Soriano et al. (2009), their results showed that red seaweed (*Gracilaria birdiae*) had high biofiltration capacity, which helps to significantly reduce concentrations of the three nutrients analyzed (PO_4–P, NH_4–N, and NO_3–N) over the study period. The concentration of PO_4–P was reduced by 93.5%, NH_4–N by 34%, and NO_3–N by 100% after the 4-week trial period. Therefore, diversifying a cultivation system, and integrating the cultivation of extracted algae with fish or shrimp farming, makes sense not only ecologically but also economically (Neori et al. 2004; Granada et al. 2016; Nederlof et al. 2022).

Sponges

The effective filtering capacity of organic matter by sponges is well proven. Also, they have the ability to produce interesting bio-commercial products. For instance, we can mention biomedical agents, biosilica, biosintering, and collagen (Muller et al. 2009; Granada et al. 2016; Gokalp et al. 2019, 2021; Varamogianni-Mamatsi et al. 2022). These issues have led us to use these sponges in IMTA systems that seem technically feasible (Schippers et al. 2012; Gokalp et al. 2021; Varamogianni-Mamatsi et al. 2022).

Evidence has been gathered that the organic diet of many sponges consists mainly of dissolved organic matter (DOM), operationally defined by all organic matter passing through a "fine" filter, typically 0.2–0.7 µm (Benner 2002). As DOM is not bioavailable as a food source to most other heterotrophic organisms, DOM feeding by sponges provides an additional benefit to their application as an extractive IMTA component. In contrast, uptake of POM only represents a minor proportion of total organic intake (de Goeij et al. 2017).

Sponges can have a considerable impact on water quality, considering the immense water processing rates of sponges (up to 50 m^3 per dm^3 of sponge tissue per day) (Weisz et al. 2008), their high particle retention efficiencies (up to 98%) (Lesser 2006). It led to the idea of using sponges to remediate organic pollution from aquaculture cages (Ledda et al. 2014; Gokalp et al. 2019). The Mediterranean sponge *Spongia officinalis* var. *adriatica* had a very high efficiency of removing bacteria (12.3×10^4 cells ml^{-1} with a maximum retention efficiency of 61%) when used in marine environmental bioremediation (Stabili et al. 2006). Similarly, the Mediterranean sponge *Aplysina aerophoba* showed high efficiencies in taking food microorganisms (bacterial isolates) from environmental water in a flow-through system (Wehrl et al. 2007). *Hymeniacidon perlevis* was able to remove pathogenic bacteria, achieving removal of 60.0–90.2% of fecal coliform bacteria, 37.6–81.6% of pathogenic *Vibrio* spp., and 45.1–83.9% of the total bacteria in a 1.5-m^3 turbot (*Scophthalmus maximus*) aquaculture system (Zhang et al. 2010). In a similar study, *H. perlevis* was able to accumulate, remediate, and metabolize halophilic *Vibrio* spp., heterotrophic bacteria, total culturable bacteria, fecal coliforms, and fecal *Streptococci* (Longo et al. 2010).

The application of BFT in IMTA

BFT has grown mainly out of shrimp and tilapia farming to increase productivity and reduce ecological impact through nutrient recycling and water usage (Khanjani et al. 2021a; 2021b). Reduced waste production and effluent mitigation also help control pathogens (El-Sayed 2021; Khanjani et al. 2022b). Although biofloc operations improve water quality for farmed species by managing water usage, the increased levels of TSS and organic matter in farming units can pose serious challenges to the surrounding environment (Ray et al. 2010; Poli et al. 2019; Khanjani and Sharifinia 2021; Khanjani and Sharifinia 2022a; 2022b). BFT can be integrated into the IMTA schemes, where the waste produced by one organism is used as food for another (Poli et al. 2019, 2021). For instance, filter feeders such as *Oreochromis* sp. and *M. liza* can be added to the system to take advantage of the TSS and the organic matter collected. The selection of the appropriate species depends on several factors, as outlined by Borges et al. (2020):

- Selected species should not compete for food.
- Consumption of suspended solids and organic matter should not harm the health of filter feeders.
- Filter feeders should not negatively impact the health and growth of other species in the system.

Borges et al. (2020) report that *M. liza* consumes organic matter in the cultivation of white shrimp (*Litopenaeus vannamei*) and subsequently reduces sludge. Another work with this species reports comparable results where the TSS discount, water quality improvement, and shrimp growth were evident (Holanda et al. 2020). In contrast, gray mullet (*M. cephalus*) is not an efficient biofloc consumer under the shrimp polyculture BFT system (Hoang et al. 2020). Such differences can be attributed to mullet species and cultivation conditions (Mugwanya et al. 2021).

A study by Costa et al. (2021) reported that the prey selectivity of *C. gasar* for flagellates reduces its effectiveness as an agent for suspended solids control in IMTA systems; however, it has been suggested that this species can be used as an effective consumer of protozoans in BFT.

Lima et al. (2021) examined the effects of *Crassostrea* sp. on the performance of *L. vannamei* during the nursery phase in a multitrophic biofloc system, and they found that stocking densities of 100 and 200 oysters/m^2 can achieve better control of nitrogenous compounds and suspended solids. Pinheiro et al. (2020) observed that integrating *L. vannamei* and *Sarcocornia ambigua* at different water salinities (16 and 24 psu) favored the elimination of N and phosphate compounds and did not negatively affect the growth of shrimp. Likewise, Legarda et al. (2021a) showed that an integrated BFT system (*L. vannamei* and *Ulva fasciata*) facilitated N and P recovery at 5.5% and 7.6%, respectively, compared to the controls (without *Ulva fasciata*).

An integrated approach for rearing Pacific white shrimp (*L. vannamei*) with red seaweed *Agarophyton tenuistipitatum* was assessed on an experimental scale in a biofloc system (Sarkar et al. 2021), and their results revealed that the incorporation of seaweed was successful to improve water quality (NH_4–N (93.73%), NO_2–N (60.04%), NO_3–N (73.38%), and PO_4–P (49.06%), growth of shrimp (increase final weigh (5.5 g), specific growth rate (5.31% day^{-1}), and survival percentage (74.17%) in the biofloc-seaweed system.

In another research conducted by Azhar et al. (2020), the production performance of biofloc-based co-culture systems of Nile tilapia (*Oreochromis niloticus*) and red claw crayfish (*Cherax quadricarinatus*) with varying carbon–nitrogen ratios (C/N) was investigated. Their results showed that an increase in the C/N ratio positively affects feed utilization efficiency and water quality in biofloc-based tilapia–red claw crayfish co-culture systems.

Nursery-based co-culture of *Penaeus indicus* along with seaweed *Gracilaria tenuistipitata* trial was done in recirculating aquaculture systems)RAS(by using BFT to evaluate the growth, survival performance, and immune potential (Das et al. 2022), and their results revealed that incorporation of macroalgae in biofloc-based RAS improves the production efficiency and immune response of shrimp during nursery phase. Better results have been obtained from a combination of the IMTA system and BFT on shrimp culture compared to the IMTA system, where an improvement in FCR, economic return, survival, and production, as well as reduction of nitrite-N and TAN were observed (Brito et al. 2014; Liu et al. 2014; Lima et al. 2021).

Control of total suspended solids

The release of suspended solids from aquaculture facilities can burden the surrounding environment, so management of suspended solids is among the challenges concerned professionals should research. High TSS reduces water quality and can lead to hypoxia and growth reduction in cultured shrimp due to gill occlusion (Ray et al. 2010; Khanjani et al. 2022a). Elevated TSS also increases energetic costs due to increased difficulty in maintaining recommended oxygen levels (Crab et al. 2012; Gaona et al. 2011; 2017; Khanjani et al. 2022c). However, the limitations of mechanical filters have encouraged research into the applications of living organisms for TSS control. In IMTA systems, organisms from different trophic levels are used to remove suspended and dissolved solids in situ (Chopin et al. 2001; Troell et al. 2009; Martínez-Espineira et al. 2015; Legarda et al. 2019; Poli et al. 2019); these species include inorganic extractive species such as micro-and macroalgae and organic extractive species such as mussels and fish from low trophic levels (Neori et al. 2007; Ekasari et al. 2014; Granada et al. 2016; David et al. 2017). Careful selection of extractive species can significantly decrease the waste produced in the system. TSS values in the 400 and 500 mg L^{-1} have been recommended for farming marine shrimp (Ray et al. 2010; Samocha et al. 2007), while Avnimelech (2009) recommends 200–500 mg L^{-1} of TSS to ensure good shrimp growth as well as water quality. Bivalves have proven to reduce TSS in the IMTA system and, therefore, can be utilized in BFT to manage flocs (Chopin et al. 2001; Gaona et al. 2016). Oyster and scallop cultivation has a long history and appears to have a promising future (Legat et al. 2017). Integrating these species into IMTA operations can enhance biomitigation, nutrient use, and sustainability (Biswas et al. 2020).

Economics of IMTA

IMTA systems are more cost-effective than mono- and polyculture farming due to improved growth of the animals and water quality, affecting all aquaculture aspects. Growth parameters and survival rate are determining factors in economic returns and the profitability of the culture operation (Khanjani and Sharifinia 2020). Increased utilization of inputs also improves efficiency and economic value. Additionally, producing more products with higher variety will bring more profit to the breeder.

External environmental costs, benefits of IMTA systems, the start-up cost of adopting IMTA, and the reduced cost of environmental externalities have been investigated and compared with figures from monoculture in some studies (Nobre et al. 2010; Knowler et al. 2020). The results showed that integrated aquaculture systems have significant benefits in a regulated economic environment that rewards a reduction of externalities.

Expensive production technologies, with negative impacts on the environment and society, can lead to a “high-value” fish being priced out of the mainstream seafood market. In contrast, it seems that low trophic-level organisms are more profitable, even though their revenue per kilogram is low, due to their low production cost and the large demand for affordable seafood. By encouraging the culture of such species, IMTA can improve the ecological efficiency of the aquaculture operation, cut production costs, and increase sustainability (Neori and Nobre 2012).

Incorporating shellfish and seaweed cultivation into monoculture farming will increase profits and offer environmental and social benefits by reducing environmental costs (Fonseca et al. 2015; Knowler et al. 2020). Different combinations of species have been evaluated for their potential to increase profits, including a combination of shrimp, oyster, and seahorse, which resulted in an internal rate of return equal to 131.1% and payback period < 2 years (Fonseca et al. 2015). Overall, IMTA systems appear to be more profitable than monoculture, which should give hope for future expansion and adoption. The IMTA approach is particularly promising in ICAM. Whitmarsh et al. (2006), Ridler et al. (2007), Nobre et al. (2010), Shi et al. (2013), and Carras et al. (2019) all suggested that higher profitability is possible with IMTA than with monoculture aquaculture.

In a study conducted by Nobre et al. (2010), The farm’s total benefit from adopting IMTA was estimated to be between USD 1.1 and 3.0 million per year; these values considered differences in profitability between monoculture and IMTA, as well as the startup cost of adopting IMTA and the value of reduced environmental externalities. The results suggest significantly increased benefits from the integrated aquaculture system in a regulatory-economic environment that rewards reductions in externalities.

In a study conducted by Carras et al. (2019), their results showed that the net financial returns from the salmon, mussel, and kelp IMTA on the east coast of Canada are superior to those from salmon monoculture when it is assumed that the quantity of salmon produced remains unchanged after IMTA adoption. This is intuitive since if mussels and kelps are added to an existing salmon monoculture operation to create an IMTA farm, with no changes to the production schedule or size of the salmon harvest, and if the revenues of mussel and kelp sales exceed their costs of production, IMTA will have a higher net present value than salmon monoculture.

There is a significant opportunity for research into the economics of IMTA systems. Previous studies disclosed three main topics: (i) economic studies on environmental externalities, (ii) financial analyses of on-site profitability, and (iii) studies from a consumer perspective on the acceptability of IMTA products and consumers’ willingness to pay for the products (Knowler et al. 2020). However, less attention has been paid to the full range of benefits provided by IMTA systems, including the societal benefits. Further studies are needed to evaluate the environmental benefits of IMTA cultivation, and the externalities associated with such systems.

Future challenges in IMTA

As IMTA systems are adopted more widely, their challenges become apparent. The current challenges face by IMTA systems are as follows (Sasikumar and Viji 2016; Rosa et al. 2020):

- Higher capital investment: due to the need for utilization of more advanced technology and engineering in open-sea farming, IMTA operations require a greater up-front investment.
- A limited number of suitable species.
- The need for careful management of inputs and nutrient flows.

- Increased area requirement: although IMTA systems lower the pressure on natural sources, and benefit the environment, there is still competition between aquaculture activities and others in coastal and marine environments. Stakeholder conflicts frequently occur, ranging from concerns about environmental impacts such as pollution to site allocation.

Prospects of marine (inshore and offshore) and land-based IMTA

By using IMTA systems, farmers, to some extent, manage wastes to achieve bioremediation and reduce the environmental impacts of culture operations. In the future, eco-friendly farming practices will receive more scientific, financial, and governmental support. Therefore, given the sensitivity and concern of the people of the world to environmental issues, systems such as the IMTA, which are environmentally friendly, will play a prominent role in the future of the world's aquaculture. A variety of new combinations of the IMTA systems with other novel culture systems will emerge in the future. An example is multitrophic recirculating aquaculture systems (MRAS). These systems have the same water usage as customary RAS systems while being more environmentally friendly due to less waste production. In MRAS, the filtration/biofiltration units are replaced with units utilizing extractive organisms. These systems also eliminate the need for waste collection ponds and produce multiple final products, each of which can create economic value (Correia et al. 2020).

These systems will grow more in the future due to its efficiency, and value creation (social and economic), and will see their expansion as much as possible, especially in third-world countries. The development of appropriate infrastructure, education, promotion, applied research, government support, and the enactment of appropriate legislation in these countries will contribute to this development. Last but not least, the development of the IMTA system from the sea (inshore and offshore) to the land and observing the development of land-based IMTA systems with new features (in terms of species combinations, engineering) will not be far from the mind. Furthermore, the development of this system in harsh environments such as deserts can significantly contribute to the development of desert aquaculture in the world, where diversifying crops and increasing the net profit of farming operations can greatly help the industry's sustainability.

Conclusions

The IMTA approach can address many of the issues associated with intensive aquaculture like eutrophication, higher disease outbreaks, growth retardation, and aquafeed ingredient shortage. In this system, the waste produced by one trophic level is used as the input for organisms in the lower levels in the form of food or fertilizer. In the IMTA systems, the fed components of the system, such as fish or shrimp, are grown in combination with extractive species such as filter feeders, detritus feeders, herbivorous fish, or seaweeds in carefully selected ratios. We expect a lot of growth for the IMTA system in the future, and its popularity will increase dramatically due to its clear economic outlook, social acceptance, and, more importantly, environmentally friendly approach. IMTA can certainly create a more sustainable future for aquaculture in light of these facts. Developed IMTA systems can contribute to environmental health, economic development, and job creation in coastal regions worldwide. Broad adoption of IMTA requires coordination between governmental and non-governmental organizations, academia, and local communities.

Acknowledgements We are grateful to game wardens that have devoted their lives to saving endangered animals and sharing their valuable data with us. We thank anonymous referees for helping to improve an earlier version of the manuscript.

Author contribution Conception and design of study and idea for the article: Mohammad Hossein Khanjani, Saeed Zahedi, Alireza Mohammadi.

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Data availability This manuscript has no data.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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