applied sciences

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Review

Lessons for Coastal Applications of IMTA as a Way towards Sustainable Development: A Review

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Abstract: Integrated multi-trophic aquaculture (IMTA) systems integrate the cultivation of species from different trophic levels. Uneaten feed, solid wastes, and dissolved nutrients are turned into harvestable and healthy food, making IMTA a driver for ecologically sustainable aquaculture. Its wider sustainability potentials arise from social, environmental, and economic sustainability enhancement options. Biological and economic outcomes are promising, while social equity and acceptance remain to be further investigated in the context of the long-term viability of aquaculture. Sustainable coastal and marine aquaculture development requires a holistic approach that involves social/cultural, economic, as well as environmental sustainability. This article examines IMTA as a pathway to socially, environmentally, and economically sustainable development. We collate evidence that shows that IMTA can minimize the negative environmental effects of aquaculture, assist local economies, and boost competitiveness and long-term economic viability. Available analyses of socio-economic and cost-effectiveness reveal positive prospects for IMTA systems, through product diversification, faster production cycles, and IMTA product prices and show a divergence between financial returns at the level of the entrepreneurial unit and economic returns at the macro level, which inhibits the uptake of IMTA. We conclude that the lack of governance analysis or inappropriateness of institutional development, in terms of aquaculture governance and management laws and regulations, is at the core of the hitherto weak engagement with IMTA. Unsuitable policies, regulations, and public and private sector decision policies and implementation, underlined by the scarcity of analyses of aquaculture governance institutions, are part of the reason for this. The evidence we have aggregated indicates that the relative scarcity of commercially successful coastal IMTA undertakings is not so much an intrinsic feature of the IMTA approach but is likely to have been generated by missing or inappropriate governance structures and procedures in the coastal realm.

Keywords: IMTA; coastal aquaculture; sustainable aquaculture; social development

Citation: Hossain, A.; Senff, P.; Glaser, M. Lessons for Coastal Applications of IMTA as a Way towards Sustainable Development: A Review. *Appl. Sci.* **2022**, *12*, 11920. https://doi.org/10.3390/app122311920

Academic Editors: Tiago Verdelhos and Ana Cristina Rocha

Received: 20 July 2022
Accepted: 6 November 2022
Published: 22 November 2022

1. Introduction

Aquaculture is the food-producing sector with the highest annual growth rate [1]. Production has increased steadily over the past three decades and will likely continue to do so in the future to ensure the needs of a more populous and affluent world [1]. Aquaculture is widely recognized as an important strategy for food security and poverty eradication [2], addressing at least seven of the 17 United Nations Sustainable Development Goals (UN SDGs) [3], and it plays an important role in ensuring human food security and nutrition in the future, as wild fisheries fail to meet the demand for aquatic products [4]. Fish contributes to around 20% of total animal protein intake [5] and is one of the cheapest sources of animal protein. Over recent decades, the contribution of aquaculture to global fish output has increased, reaching 82.1 million tons (46%) of the estimated 179 million tons of global production in 2020, and this is expected to rise to 53% by 2030 [4]. This is mostly due to the commercialization of farm-raised aquatic animals such as shrimp, salmon, bivalves, tilapia, and catfish [6]. With the growing scarcity of freshwater, aquaculture growth may increasingly occur in marine and coastal environments. Ongoing environmental change processes, global population growth, and fisheries and food availability trends also imply a steadily increasing role for coastal aquaculture across the globe. This has raised concerns about environmental consequences and conflicts of aquaculture with other coastal uses in Europe, North America, Australia, and Asia [6]. At the same time, the available space for coastal aquaculture is altering: by 2080, sea level rise is expected to have turned approximately twenty percent of coastal wetlands into marine spaces [7].

The use and wastage of aquaculture feeds can negatively affect surrounding ecosystems. Feed waste and faecal production contribute to significant organic matter and nutrient loadings in marine and coastal ecosystems. Feed wastage can reach up to 38%, and this is one of the most significant sources of pollution [8,9]. Several countries have also imposed restrictions on the practice of chemotherapeutic agents and reduced the use of feed additives, such as antibiotics and oil, in aquaculture feeds [10,11], rendering classical single cultivar aquaculture less viable. Nonetheless, current aquaculture practices cause the eutrophication of coastal and other aquatic systems [12]. It is important to increase the understanding of how intensive and single species (monocultural) aquaculture generates deleterious environmental and social impacts. This has raised interest in ecosystem-based aquaculture such as integrated multi-trophic aquaculture (IMTA) [13,14].

IMTA integrates aquatic organisms from various trophic levels in order to mimic ecosystem functions (Figure 1) [15–19]. Waste material from production in higher trophic layers (i.e., of finfish and crustaceans) serves as food for organisms cultivated at lower trophic levels that transform the otherwise wasted and polluting resources into valuable products. Waste is thus minimized or eliminated and the overall productivity of the food system boosted [20–22]. It has been argued that IMTA is capable of supporting ecologically, environmentally, and socially viable aquaculture with economic viability [23]. By using the by-products of some cultivars to produce further useable or marketable plants and animals, it may support ecological sustainability through biomitigation, economic security through product diversification and risk mitigation, societal acceptance through better management, and social sustainability through a wider spread of aquaculture benefits than what is possible through conventional aquaculture. The main potentials of IMTA are thus environmental neutrality, economic viability, and social sustainability [24], although MTA can improve the long-term viability of aquaculture by generating environmental, economic, and social benefits. All this notwithstanding, implementation over the past decades has been low [16,25]. The objective of this paper is to collect the widely dispersed studies that analyse the sustainability potentials resulting from the combination of social, environmental, and economic potentials related to IMTA.

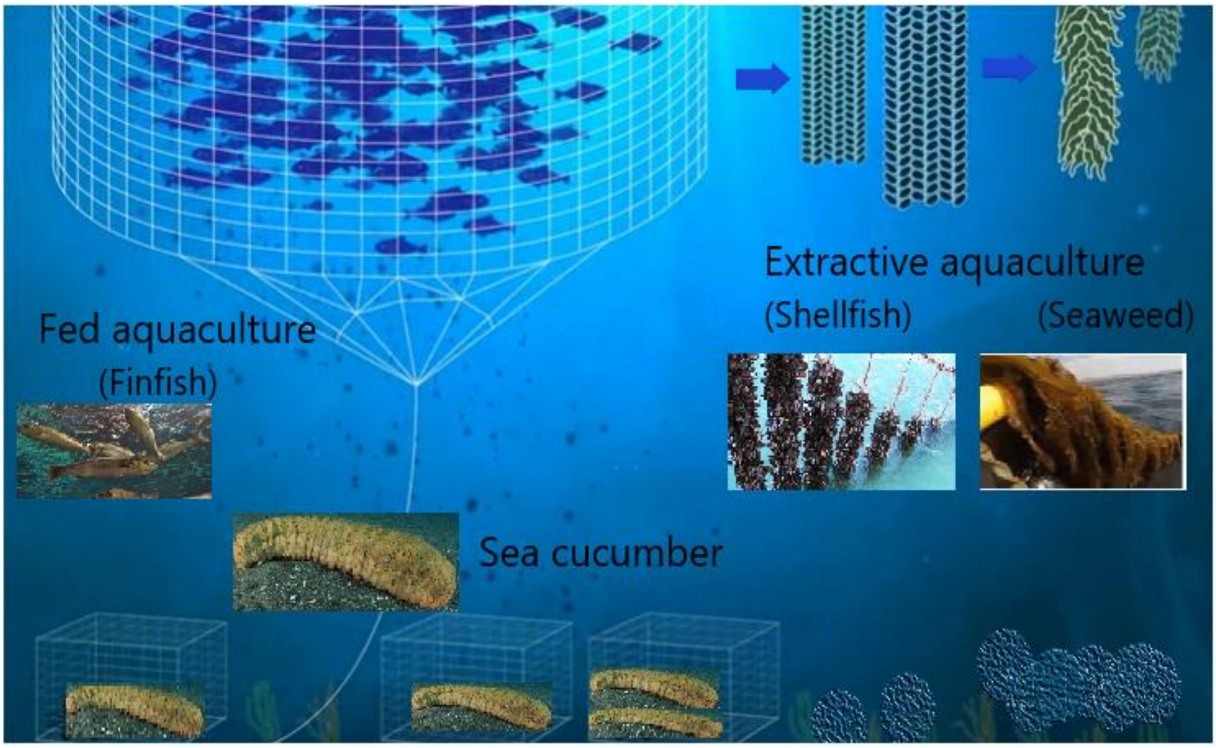

Figure 1. An integrated multi-trophic aquaculture (IMTA) facility: combination of fed aquaculture (e.g., finfish) and organic extractive fish farming (e.g., shellfish, seaweed), takes advantage of particulate organic matter via extractive cultivars (e.g., seaweed) that absorb the benefits of dissolved inorganic nutrient enrichment (Redrawn from IMPAQT H2020 Project) [26].

2. Methods

This study is based on a literature analysis. Published literature was identified in a literature search performed with Google Scholar web search using the "Publish or Perish" software (version: 7.33.3388.7819) [27]. The specific keywords used were "IMTA"; "coastal aquaculture"; "sustainable aquaculture"; "social development". These were separately inserted and searched. We extracted 187 relevant papers, discarded irrelevant ones by perusing the abstracts and read 57 of the papers initially found in the search related to these keywords. With "snowball system", additional literature identified upon reading this first batch of publications was also included, as well as related publications known to the authors.

3. Sustainability Potentials of IMTA

The interconnected spheres of sustainability (Figure 2) are well known. They include the social, economic, and environmental [28]. This concept can be applied to IMTA and other forms of resource management [29]. For over two decades it has been suggested that IMTA can render production more sustainable by reducing the environmental effects of intensive aquaculture operations, and by generating financial benefits to aquaculture producers through product diversification, faster production cycles, and higher prices for IMTA products [13,24,30–32].

As discussed above, IMTA appears to be an appropriate method for developing economically viable and socially beneficial coastal aquaculture. Despite some successful pilot work (Table 1), IMTA development has hardly incentivized the commercial engagement of private sector actors, however, with China as the main exception. In the following, we present currently available evidence to explain why this might be the case.

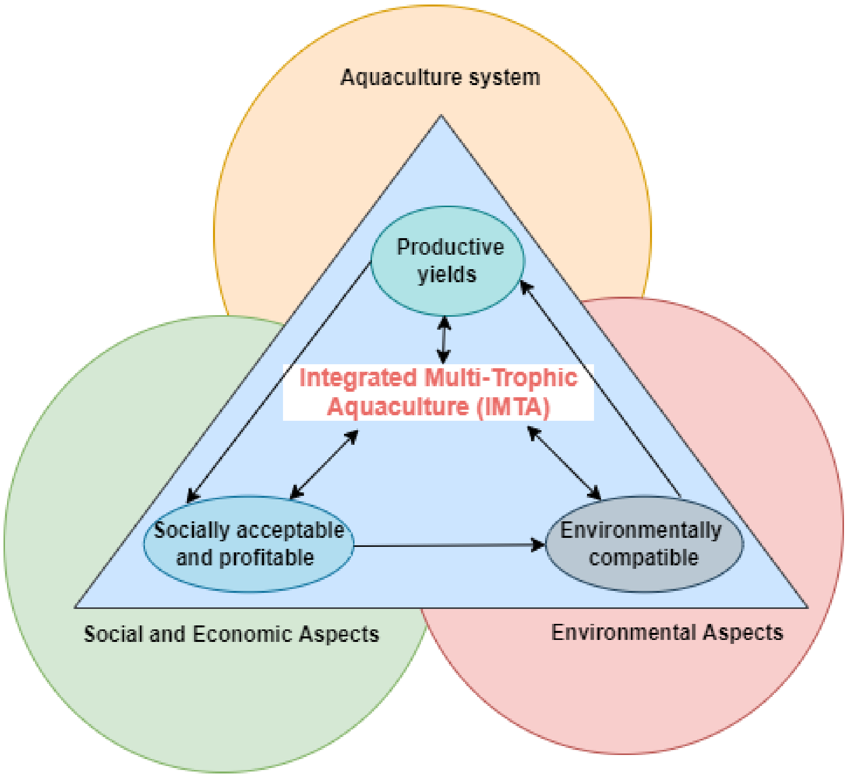

Figure 2. Sustainability in the context of IMTA (Adopted from [28]).

Table 1. Examples of integrated or other ecosystem-based aquaculture developments (Source: [33,34]).

Region/Countries	Aquaculture Ecosystems	References
Asia (China, Thailand. Cambodia, Vietnam, Indonesia)	Integrated aquaculture benefits millions of rural people.	[35]
Asia (China)	Bioremediation and an increase in total yields of up to fifty percent can be achieved with IMTA, which combines fish, shellfish, and seaweed.	[36]
Canada	Cooke Aquaculture, the largest salmon aquaculture company in eastern Canada, embraced integrated multi-trophic aquaculture.	[20,30,37]
South Africa	Numerous abalone farms using seaweed to filter effluent water and substitute commercial feed.	[33]

3.1. Environmental Sustainability

Population growth increases demand for food, but global resources cannot indefinitely satisfy this demand [38]. Environmental sustainability is concerned with pollution control, the wise and effective use of natural resources, ecosystem integrity and the carrying capacity of the natural environment [39]. One of the most harmful environmental effects of coastal aquaculture is the release of polluted effluents containing uneaten feed and faeces. By increasing nutrients in the water, particularly nitrogen and phosphorus, a phenomenon also denominated as "organic enrichment", it degrades receiving water bodies and sediments [40]. IMTA may turn aquaculture more sustainable by removing nitrogen and phosphorus from the water column, thus mitigating eutrophication and lowering biological degradation risks [41]. Improved coastal aquaculture waste management also reduces the risk of disease transmission and allows for higher quality production by improving water quality. The treatment of wastes from aquaculture requires the development of sustainable coastal aquaculture. The utilization of IMTA systems and the microbial nitrification and denitrification that occurs in sediments play an important role here [40,41].

Assimilative biofiltration by algae increases the environmental capacity for nutrient assimilation. Macroalgae are an efficient instrument for bioremediation because they can absorb anthropogenic nutrients [40]. Seaweeds are best suited for biofiltration since they have the highest productivity of all plants, as well as high economic potential [21]. An Atlantic Coast IMTA study that focuses on algae (Rhodophyta) with fish (turbot *Scophthalmus maximus*, and sea bass *Dicentrarchus labrax*), also identified algae as great candidates for biofiltering and wastewater reduction [24]. Research has also been conducted on *Gracilaria bursa-pastoris*, *Gracilaria gracilis*, *Chondrus crispus*, *Palmaria palmata*, *Porphyra dioica*, *Asparagopsis armata*, *Gracilariopsis longissima*, *Ulva rotundata* (Rhodophyta), and *Ulva intestinalis* (Chlorophyta) as biofiltration in IMTA approaches. Experimental studies have continued on the integration of algae with sea bass and turbot [42,43]. *Gracilaria bursa pastoris* had the best yields and nitrogen absorption efficiency of the three species examined (*Gracilaria bursa pastoris*, *Chondrus crispus*, and *Palmaria palmata*), and was thus recommended as the best choice for integration with sea bass or turbot [43]. *Ulva rotundata*, *Ulva intestinalis*, *and Gracilaria gracilis* were co-cultivated with sea bass and found to be effective biofilters of phosphate (PO_4^{3-}) and ammonium (NH_4^+) from waste waters [44].

3.2. Economic Sustainability

Economic sustainability requires the use, recycling, and protection of human and material resources in ways which create sustainable values over the longer term [45]. Economic sustainability also calls for a production system that meets consumption needs without jeopardizing future requirements [46]. Human life on Earth is nourished and perpetuated by utilizing the limited natural resources available [47]. The profit component of sustainability is concerned with achieving economic growth, resource efficiency, and the financial viability of businesses [48].

Blue mussel (*Mytilus edulis*) near commercial salmon farms in the Bay of Fundy, Canada, developed 20 percent faster than those at reference locations further away, indicating that harvested mussel production is higher in an integrated aquaculture system than in a monocultural one [49]. Evidence from the BIOFAQs project on the west coast of Scotland supports this. Here, mussel growth was considerably higher at a site within 10 m of a salmon farm than at a control site 500 m away [50]. The mussel lines acted as in situ biofilters, and increased growth of the mussels was linked to the use of organic waste from the salmon farm. Economic research has focused on the diversity of benefits for growers, consumers, and society that result from the implementation of IMTA systems [51]. A study of South African abalone farming shows that IMTA can stabilize seafood supply by increasing product diversity and reducing market risks from price volatility, as well as increase job diversity by providing high-pay jobs for trained personnel while offering lower-pay jobs for untrained people in peripheral locations [37]. Invertebrates, seaweeds, and detritivorous fish may be economically beneficial in terms of supplying local consumption needs, while high-value fish and shrimp are exported for foreign currency. Implementing IMTA improves waste assimilation capabilities at farm level and in the wider environment. This may be a main reason why IMTA today is practised most widely in China [52,53].

3.3. Social Sustainability

Social sustainability has been conceptualized to include equity, empowerment, access, involvement, cultural identity, and institutional stability [54]. It has also been related to poverty reduction and deemed essential to help achieve a meaningful life by focusing on sound health care, nutrition, education, peace, and stability around the globe [55,56]. Social sustainability has also been related to human rights, gender equity, public engagement and participation, and the rule of law in promoting peace and social stability for sustainable development [57,58]. A conceptual framework for elaborating context-specific working definitions of the social dimension in ecosystem management comprises seven criteria: (1) population and resource use; (2) poverty, basic needs and well-being; (3) equity and justice; (4) social and human capital; (5) participation, management and governance;

(6) resilience, vulnerability, and adaptive capacity; and (7) collaborative learning and reflexivity [59,60]. The Sustainable Europe Research Institute [61] proposes that social sustainability is "a distinct feature of sustainable development that is equally as vital as the economic or environmental dimensions", but that it is still underappreciated by scientists and policymakers alike. In economic and environmental systems, flows and cycles tend to be readily observable. In contrast, social interactions can be more intangible and more difficult to model [62,63]. Sustainable development in agriculture, forestry, fisheries and also in aquaculture conserves land, water, plant, and animal resources while remaining environmentally non-degrading, technically feasible, economically successful, and socially equitable and benign and socially acceptable [64]. Aquaculture is a diversified industry and its effects, particularly on the environment, vary with species, farming methods, local environmental conditions, and socioeconomic context [65].

Fish farms employ 18.7 million people worldwide, and this number rises three- to four-fold when secondary and post-harvest jobs are factored in [66]. Each employed person supports up to four dependents [67]. Aquaculture is thus a major contributor to global welfare, providing jobs and the potential for positive social change. It can result in enormous societal advantages in terms of food production, infrastructural development, and employment possibilities (e.g., India, Bangladesh) [68]. However, there is still a lot of contextual heterogeneity among communities when it comes to aquaculture [68], and many key concerns remain unsolved. Finfish aquaculture appears to have a greater positive impact than rope mussel farming; however, the latter can hold important cultural values and contributes to place-based understanding, connecting people with place and identity, and thus, it plays a critical role in the preservation of the working waterfront identity [69].

Most knowledge of aquaculture's social effects is produced in the Global South. In industrialized Global North countries, aquaculture generates employment and infrastructure, particularly in rural areas. Here, aquaculture suffers from a lack of high-paying employment opportunities and workers willing to accept low-paying menial positions. There have been only a few sociological studies conducted on aquaculture in the Global North [70], while research continues to focus on economic and societal conflicts surrounding resource utilization and environmental concerns in the Global South. This has promoted regulatory responses that are becoming more rigorous and expensive [71,72]. The concept of "social license", defined as "the needs and expectations on a business by neighborhoods, environmental groups, community members", is gaining importance in democratic countries of the Global North [73]. Studies on the social and economic impacts of aquaculture that are conducted with a broad range of stakeholders contribute to better understanding of and, consequently, a higher level of trust in aquaculture activities across the globe [74].

Aquaculture has negative social impacts if it contracts or collapses, for instance, because of disease outbreaks, food safety issues, or natural disasters [75]. As coastal aquaculture expands, new expertise is needed to comprehend environmental and social implications and develop new cultivation techniques on the basis of integrated system understanding [76]. A contextualized systems perspective [77] is needed to identify the diverse sustainability implications of an intervention such as IMTA [78]. A recent study on Canadian customers' views of IMTA products identifies "double needs" among consumers: firstly, to consume the purchased product; secondly, for the production and consumption of the purchased product to safeguard the natural environment. The same study finds that consumers were more interested in the "usefulness" of IMTA products than in their price or quality [79,80]. Environmentalism (understood as environmental concern and 'perceived consumer effectiveness' (PCE) [79], refers to how confident a consumer is that they can obtain the results they want and value [81]). This "perceived social welfare" was found to affect purchasing behaviour. This study supports a better understanding of consumer attitudes toward environmentally friendly aquaculture products by examining the effect of perceived social welfare as an independent, explanatory variable.

4. Candidate Species for Coastal IMTA

Various marine organisms at lower trophic levels have been tested alongside fed species in IMTA (Table 2) as extractive species and/or additional crops. All elements of cultivation have commercial value as well as significant roles in re-utilizing and bio-mitigation services. Diversifying aquaculture is recommended for the sake of lowering economic risk, increasing sustainability, and enhancing competitiveness. In an ecological context, diversification can also include cultivating species from different trophic levels, such as seaweeds, shellfish, crabs, echinoderms, worms, polychaetes, sponges and macroalgae, and bacteria that have been chosen for their complementary roles in the ecosystem [82–84]. The environmental, biological, physical, chemical, social, and economic contexts in which IMTA systems are deployed inform the numerous possible variants that might be built on the basis of IMTA as the central/overarching subject.

Table 2. Examples of species at low trophic levels investigated as extractive or additional species alongside fed species in IMTA experiments.

Extractive/Additional Species	Fed Species	Reference
Algae		
Gracilaria chouae	*Sparus macrocephalus* (black sea bream)	[85]
Laminaria saccharina	*Salmo salar* (Atlantic salmon)	
Gracilaria sp.	*Feneropenaeus indicus*	[6]
Gracilaria sp.	fish (not specified)	[83]
Kappaphycus alvarezii	*Rachycentron canadum* (cobia)	[6]
Chaetomorpha linum *Gracilaria bursa-pastoris*	*Dicentrarchus labrax* (European sea bass) *Sparus aurata* (sea bream)	[82]
Bivalves		
Mytilus edulis (blue mussel)	*Salmo salar* (Atlantic salmon)	[86]
Mytilus galloprovincialis	*Dicentrarchus labrax* (sea bass) *Sparus aurata* (sea bream)	[87]
Mytilus galloprovincialis	fish (not specified)	[84]
Echinoderms		
Apostichopus japonics (sea cucumber)	Red sea bream	[88]
Apostichopus japonics (sea cucumber)	fish (not specified)	[83]
Parastichopus californicus (sea cucumber)	*Anoplopoma fimbria* (sable fish)	[89]
Cucumaria frondose (sea cucumber)	*Salmo salar* (Atlantic salmon)	[90]
Australostichopus mollis (sea cucumber)	*Perna canaliculus* (green-lipped mussel)	[91]
Decapods		
Homarus gammarus (European lobster)	*Salmo salar* (Atlantic salmon)	[92]
Polychaetes		
Sabella spallanzanii	*Dicentrarchus labrax* (European sea bass)	[93]
Sabella spallanzanii	*Dicentrarchus labrax* (European sea bass) *Sparus aurata* (sea bream)	[82]
Marphysa sp. (mud polychaete)	fish (not specified)	[94]
Sponges		
Hymeniacidon perlevis	fish (not specified)	[84]
Sarcotragus spinosulus	*Dicentrarchus labrax* (European sea bass) *Sparus aurata* (sea bream)	[82]
Halisarca caerulea	fish (not specified)	[83]
Fish		
Mugil cephalus (grey mullet)	*Sparus aurata* (gilthead sea bream)	[95]

5. Economic Value and Financial Viability of Coastal IMTA

5.1. Species-Specific IMTA

Sea cucumber (*Cucumaria frondosa)* aquaculture has grown in popularity in a context of rising demand and declining wild fisheries, aided by technological advance in the production of sea cucumbers [96,97]. As detritus feeders that consume organic matter in the sediment, and as key surface sediment processors, sea cucumbers are interesting for IMTA [88,91]. Various species have shown potential when cultivated in the water column underneath fish cages [88], in cages with sea urchins [98], in abalone tanks [99], and in hanging scallop lantern nets [36]. The integration of sea cucumbers into existing aquaculture facilities could deliver significant economic and environmental benefits if appropriate culture methods are taken and if the sustainable development of the industry is supported by supporting legislative frameworks [100].

A number of studies indicate that when cultivated with salmon, shellfish (e.g., oysters and mussels) show significantly increased growth rates [86,101,102]. Regulatory services from bivalves in IMTA are also considerable [103]. If current trends continue [24], opportunities for developing novel IMTA configurations with a central role for bivalves are likely to be developed in China.

Seaweed has a big market as food, phycocolloids, feed supplements, agrichemicals, nutraceuticals, and pharmaceuticals, with a value of USD 6.4B from sales of nearly 23.8 million tons in 2012 alone [104,105]. Diversifying the culture system and implementing fish/shrimp in combination with extractive algae implies not only ecological but economic gains [21]. In 2013, China consumed 193,705 tons of its domestic sea cucumber production, while only a few hundred tons were exported. *A. japonicus* is a highly valued species in certain parts of Asia that is traded worldwide.

Using a mass balance framework [106], it was found that a ton of salmon produces about 50 kg of nitrogen, which is released into the environment in the salmon production cycle, providing nutrients for ten tons of seaweed or five tons of mussels [107]. If we define productivity not in terms of per unit of feed (biotic depletion), but in terms of per unit of fish meal or fish oil from wild fish stocks, the recycling of otherwise wasted nitrogen into the marine proteins and lipids needed to feed fish offers opportunities to increase productivity in a way that may be economically meaningful to the farmer. Such reintegration of nitrogen into fish feed offers opportunities to increase productivity [19]. The 10 tons of algae produced per ton of fish can generate 164 kg of protein and 9 kg of marine lipids [108], and these components could be recycled as fish feed [19]. While this reduces the impact of aquaculture on the environment, it also offers so far underexplored potential for increasing the economic viability of aquaculture enterprises [19].

Using a discounted cash flow method financial returns were projected for: (i) conventional Atlantic salmon monoculture; (ii) Atlantic salmon IMTA with *Mytilus edulis* (blue mussel) and IMTA with *Saccharina latissimi* (kelp); and (iii) blue mussel, kelp, Atlantic salmon, and green sea urchin (*Strongylocentrotus droebachiensis*) as a benthic component below the net pens. The three-species IMTA was found to be significantly more profitable than the Atlantic salmon monoculture and the four-species IMTA. The four-species IMTA produced lower NPV than salmon monoculture, unless IMTA salmon and mussels were priced 10% higher. When a 10% price premium for IMTA salmon and mussels was included, both the three- and four-species generated a significantly higher NPV than salmon monoculture [37,109]. Given that the studies below indicate that price premiums on IMTA products have a bright future, it is plausible to regard the NPV projections with a 10% price premium as more reliable.

Related research on the economic viability of IMTA models that incorporate shellfish and/or algae into traditional methods of salmon monoculture also finds potential for increased farm revenues and positive social and environmental outcomes [69,110]. Salmon is at the core of the most widely used and studied IMTA systems, but the viability of other key IMTA species has also been assessed. An analysis of the financial returns generated by an integrated shrimp–oyster IMTA system that also included a seahorse production component finds that the benefit per dollar spent was approximately USD 20, with an internal rate of return of 131 percent [111]. Such results appear promising.

Farm-level financial returns within a specific regulatory context, rather than overall economic benefits from IMTA, are likely to be the central driver for the entrepreneurial decision of whether to implement IMTA. Most economic research therefore examines the viability of IMTA at the level of the farm. One study constructs a mathematical model on spreadsheet program (Quattro Pro, Borland, Inc.) of an integrated salmon–seaweed system and assesses the financial profitability of growing seaweed near salmon culture operations. The researchers examine two seaweed species, *Saccharina latissima* and *Nereocystis luetkeana*, cultivated in different parts of the farm, either between rows of salmon cages or 30 m from the back of the farm. Both species are reported as financially profitable when co-cultivated with salmon at most locations [112].

IMTA has been found able to boost individual income in favourable market conditions and to provide economic resilience in challenging times [32,37]. Research to date has focused on markets across North America and Canada, with European markets receiving attention more recently. Consumers looking for IMTA products in Eastern Canada took food safety into consideration and viewed IMTA items as safe; around half of those surveyed in one study indicated their readiness to pay an additional 10% for IMTA-labeled products [24]. It was also observed that mussels produced in IMTA systems may benefit from a price premium, which people in the New York market are willing to pay [113].

5.2. Region- and Country-Specific IMTA

5.2.1. China

MTA application is moving forward in Canada, the USA, France, Spain, Italy, and Chile [52]. While most IMTA systems so far have remained experimental, cases of commercial implementation of IMTA exist in China. In China, The Zhangzidao Fishery Group Co., Ltd. has been granted permission to cultivate scallops (*Patinopecten yessoensis*), arkshell (*Scapharca broughtonii*), sea cucumber (*Apostichopus japonicus*), and abalone (*Haliotis discus hannai*) on up to 40,000 hectares. The business has operated for over a decade, with a reported harvest of 28,000 tonnes in 2005, which was valued at over USD 60M and rendered a reported USD 18M of net profit [24]. This company is now considering seaweed farming and the creation of artificial reefs in offshore areas to improve ecological conditions and the operation’s long-term viability. In Sungo Bay (China), a company operates on an industrial scale, producing *Laminaria japonica* kelp with *Chlamys farreri*, abalone (*H. discushannai*), and blue mussel (*Mytilus edulis*). Several studies evaluate the environmental costs and benefits of Chinese aquaculture. It was examined how IMTA systems affected four ecosystem services: food security, oxygen production, climate regulation, and water treatment [114]. Using a standard cost-benefit assessment (CBA) approach, the authors find that mariculture in Sanggou Bay had a broadly positive impact on ecosystem outcomes, which account for the majority of the profits and costs associated with mariculture activities (including both economic and ecological contribution and loss). For instance, increasing the value of food production shows economic benefit, while decreasing the value of some ecosystem services results in environmental degradation. Importantly, a comprehensive assessment shows that IMTA is more economically and environmentally sustainable than two monoculture techniques for the same region; hence, they recommend it for open-water systems in China [31].

5.2.2. Others Region

In the Mediterranean, the combination of mariculture with ecological restoration suggests inshore IMTA practices and the combination of mussel farming with artificial reefs in the open sea [115]. Polychaetes, sponges, and macroalgae co-cultured in a southern Italian in-shore mariculture plant were the subject of the above-cited recent study on one of the first attempts at IMTA in the Mediterranean region [82]. In Canada, (Fundy Bay), IMTA combines kelp *Saccharina latissima* and *Alaria esculenta* with Atlantic salmon and blue mussel. Higher kelp and mussel growth rates were found with positive implications for the profitability of this enterprise [116]. In South Africa, several commercial abalone farms have successfully applied *Ulva* macroalgae to absorb ammonia from effluent water in recirculating or flow-through systems. The algae can subsequently be fed back to the abalone to supplement formulated feed [33].

A recent study considers a productive area of 2000 m^2 as representing a typical small-scale multi-trophic production system enterprise in Southeast Brazil and evaluates its economic viability with economic indicators for two monotrophic crops, *Perna perna* (mussels) and *Rachycentron canadum* (cobias). Profitability is assessed with the Internal Rate of Return (IRR), Payback Period (PP), and Net Present Value (NPV). IRR is used for financial analysis to estimate the profitability of potential investments. PP is the number of years required to recover the original cash investment. NPV compares the initial capital investment of a project to the present value of all the cash flows it will generate in the future. Investment assessments with a 10-year time horizon are undertaken using scenarios which assume 20% and 40% of cobia juvenile unit prices, average feed price, cobia commercial price, mussel commercial price, cobia productivity, and mussel productivity. In all scenarios, multi-trophic systems were more economically viable than the other evaluated scenarios. IMTA systems' greater resilience also makes them more appealing to entrepreneurs than monocultures, since diversified production is less exposed to overall failure [117].

On the southern coast of Brazil, the economic viability of IMTA (*Perna perna*) mussel, *Nodipecten nodosus* scallop, and *Kappaphycus alvarezii* algae) was assessed for a small-scale family production system of 0.4 ha. All key indicators showed positive values: Investment, operational expenses, and profitability; the financial indicators of Gross Revenue (GR) and Operating Profit (OP); the profitability indicators of Gross Margin (GM) and Profitability Index (PI), ("Gross Revenue (GR)" (which is total revenue before any deductions for expenses or losses); "Operating Profit (OP)" (which is the total amount of money made by the business in a given time period, before interest and taxes are removed); an finally also the "Profitability Index (PI)" which indicates the relationship between a proposed project's expenses and benefits). The payback period in the worst evaluated scenario was 4.24 years, and even this was still classed as a low-risk investment. Returns were always higher than the nominal discount rate of 6%. All this showed the IMTA project to be economically viable. The economic evaluation of the first experience of a small-scale commercial IMTA system in Southeast Brazil was thus positive, IMTA was shown to be able to support social and economic improvement in that region [118].

Another early study [119] in Latin America, analysed *Gracilaria chilensis* with salmon farming in an integrated salmon–seaweed production process throughout southern Chile. Seaweed production provided 34,000 USD/year of farm gross income, which is approximately USD 0.28 per kilogram of fish. The study concludes that this IMTA system brought large economic benefits to Chile's salmon farming industry, as well as clear environmental benefits. When combined with the finfish farming of cobia *Rachycentron canadum* along India's east coast, the use of IMTA in open sea cage farming resulted in a 50 percent increase in seaweed output, *Kappaphycus alvarezii* [6].

Similarly, an evaluation of the financial viability of a salmon–mussel production system on the Scottish coast was based on information from Scottish mussels and salmon culture farms without seaweed. Researchers evaluated the Net Present Value (NPV) of three different cultivation systems over a period of twenty years using the capital budgeting approach. These cultivation systems were salmon monoculture, mussel monoculture, and integrated salmon-mussel farming. The measured NPV for the USD 2.63M for the integrated salmon-mussel system was higher than the combined NPVs for both the salmon monoculture system (USD 1.7M) and the mussel monoculture system (USD 0.650M), assuming that the mussel production rate for the integrated system was 20% higher. The higher profitability of the integrated system was susceptible to changes in product prices. Even assuming that mussel prices remain constant, a 2% annual decline in salmon prices would more than offset the benefits of integration and make polyculture an unattractive investment [32].

Related results from a study of 80 farmers on the profitability of shrimp culture with tilapia on the North Central coast of Vietnam indicates that farmers using this integrated polyculture technique realized higher economic gains and lower feed and pond preparation expenses than those using non-integrative practices. Farmers also perceived that the integration of shrimp and tilapia improved their adaptive capacity in the face of weather-related shocks [120].

Available research on the economic value and financial viability at the farm level has, for a considerable period, indicated good wider economic and farm-level potentials for integrated aquaculture, and for IMTA in particular.

6. Bioremediation by Extractive/Additional Species

Bioremediation through integrated, ecosystem-based aquaculture is an important potential of integrated cultivation [6]. In recent years, water quality difficulties created by aquaculture wastes have received much interest [21,40,121]. On its own, the application of biofilters (sea cucumber bivalves) to mitigate effluents can increase economic benefits. In integrated aquaculture, waste nutrients are not a burden but a resource for the supplementary cultivation of products that also act as biofilters. Verongiida marine demosponges are a material science and marine pharmacological gold mine [122]. Sustainable approaches to construction can use Verongiida demosponges' biomaterial, and there is anti-cancer therapeutic potential. The co-cultivation of Verongiida (*Aplysina aerophoba*) in IMTA systems could thus be a viable option to improve both ecological sustainability and profit at the farm level [123,124].

Bivalves are a top candidate as extractive species in IMTA [125]. They catch waste particles from agricultural effluent and extract waste products from a higher trophic level (e.g., bacteria, phytoplankton). Grown together, *Gracilaria* sp. and *Feneropenaeus indicus* at different stocking densities showed that the seaweed removes nutrients from shrimp farm waste. 600g of seaweed removed 25% of ammonia, 22% of nitrate, and 14% of phosphate from 200g of shrimp waste at a 3:1 ratio of *Gracilaria* sp. and *Feneropenaeus indicus* [6]. Bivalves are biocontrollers of sludge for fish farms and other sources of eutrophication. The capacity of *Diplodon chilensis* freshwater mussel to mitigate chlorophyll a, phosphate, and ammonia in salmon tanks has been demonstrated [126]. *Cucumaria frondosa* exhibits a high absorption efficiency (>80%) when exposed to higher organic particulate matter, such as salmon food and faeces, so that it is an effective organic extractive species for IMTA systems. Bivalve cultivation can, therefore, be combined with fish farming to reduce the negative effects on the environment, while simultaneously offering a commercially successful crop for farmers [86].

Bivalves such as mussels, oysters, and clams as bio-filters in estuaries have shown a positive effect on nutrient-rich effluents. In IMTA, the cultivation of bivalves (*Crassostrea madrasensis*) and finfish (*Etroplus suratensis*) effectively controlled eutrophication [127,128]. The filter-feeding oysters enhanced the water quality in the farming region, consequently lowering eutrophication. In this farming technique, the best ratio of fish to oysters reported for co-cultivation was 1:0.5 [127,128].

A study on the integrated cultivation of macroalgae (*Saccharina latisima*) and mussels (*Mytilus galloprovincialis*) in the Sea of Galicia, Spain found that it was more productive than individual crops, and therefore IMTA systems could serve to diversify aquaculture and reduce environmental impact. Mussels' metabolism produces organic and inorganic waste. Mollusc-excreted ammonia helps algae thrive and improves water quality [129].

In order to develop such bioremediation systems, it is essential to choose suitable seaweed species. In IMTA, seaweeds can mitigate the environmental impact of nitrogen-rich effluents on coastal ecosystems. The seasonal distribution and productivity of seaweeds are influenced by water temperature and photoperiod [130]. In a study in Korea, (Zagalchi, Busan) [130], identify, *Codium fragile* as an ideal candidate for summer IMTA because it grows during late summer and early fall and thus should be able to absorb substantial amounts of nutrients from fed aquaculture when water temperatures are warmer.

Another study argues that it is difficult to analyse the bio-mitigation effect of extractive species in open-water studies because the Initial Biomass Ratio (IBR) of the extractive to target species is too small. This makes it difficult to conduct experiments. It is necessary to conduct an IMTA experiment on a large scale that is optimally designed and in which the Initial Biomass Ratio (IBR) of the extractive species to the target species [121].

7. Social Sustainability, Social License, and Aquaculture Governance

Social license, the approval of aquaculture plans by affected communities, is an important element of the social sustainability of aquaculture, and it holds untapped potential for holistically sustainable aquaculture. Public acceptance of IMTA depends on perceptions of the economic or social benefits and harms associated with the activity [131]. A positive association between improved environmental performance, increased social license, and better access to aquaculture licenses was shown in Norway, where the government established 45 'green aquaculture' licenses in 2013 [132]. Denmark has legislation to reduce environmental emissions from aquaculture, which encourages IMTA development [107]. However, these are small beginnings.

A more recent study in Norway confirms that IMTA can reduce the negative environmental effects of salmon aquaculture, but importantly, this first interdisciplinary study on IMTA in the region also finds that Norwegian aquaculture governance, i.e., the country's rules and laws prevent this. To assess the future of IMTA in Norway, this study conducted a workshop in which participants conceptualized IMTA for the Norwegian salmon industry. The results show that IMTA would improve public perceptions of salmon aquaculture, create skilled jobs in coastal communities, and provide the industry with new sustainable sources of marine ingredients for feed. Participants also identified that IMTA proponents face opposition from policymakers, from a public concerned about the environmental impact of salmon farming, from coastal communities that have the power to regulate access to marine territories, and from a powerful aquaculture industry that is focused on salmon production only. Agenda setting with policy and lawmakers and public opinion outreach work are clearly identified as central future tasks on the path towards viable IMTA implementation [133].

Exploring this further, a set of open-ended interviews with 34 farmers and scientists from 12 European countries who all had extensive IMTA experience identified nine types of barriers to IMTA: Biological, Conflicts, Environmental, Interest, Legislation, Market, Operational, Research & Development, and Vandalism. While the relative importance of factors varied across Europe, highlighting the need for country and site-specific measures [134], factors such as conflicts, legislation, markets, operational, and even vandalism indicate that aquaculture governance is a major field of needed engagement if IMTA is to realize its clearly documented economic and ecological potentials.

In their early global review on IMTA in temperate marine waters Barrington and coauthors [24], also discuss the social perception of IMTA as a new idea in aquaculture; finding that many people believed that IMTA was able to reduce salmon farming's environmental impact, increase financial benefits to communities, and enhance the productivity and long-term viability of enterprises. A total of 90% of the general public and 89% of aquaculture industry-related respondents in this 12-year-old study thought that IMTA might be a profitable venture. It was also found that 82% of the public and 79% of the industry believed that existing salmon monoculture methods had a moderate to negative impact on the community while IMTA was anticipated to be less harmful [37]. Positive public views of IMTA and the demonstrated willingness to pay extra for IMTA products in key markets bodes well for IMTA profit margins and should enable IMTA application. Given appropriate legislation and equity-oriented product labelling (i.e., appropriate aquaculture governance), IMTA should also be able to promote social development.

In practice, and despite clear evidence that it increases system output and promotes environmental, economic, and social sustainability, IMTA has entered the commercial realm only in a few cases. A 2021 survey of 47 countries finds that for farmers who reported using integrated multi-trophic aquaculture (IMTA), it may enhance resilience to multiple stressors by providing different market options during the COVID-19 pandemic [135]. Some authors also argue that public perceptions of IMTA are positive so that it might serve to facilitate operating permits from the government and communication with NGOs and local communities [136].

8. Conclusions

Sustainable coastal development requires a holistic strategy that considers social, cultural, economic, environmental and governance aspects [137,138]. This means a balance between good environmental quality, which provides ecosystem services, inclusive social development, and an economic system that prioritizes human well-being in a just and participatory governance framework over limitless growth [137,139,140]. IMTA has been repeatedly shown to be an economically viable and socially beneficial approach to coastal aquaculture. As monoculture is hampered by high input costs (such as electricity, medicine, and feed), environmental challenges (such as worsening waste and water quality), and social and economic concerns (such as vulnerability to shocks and loss of low-cost local protein sources), these IMTA potentials become ever more valuable. Aquaculture governance is a subject of increasing importance [72]. As recent work indicates, however, the study and practice of aquaculture governance [141,142] as yet does little to support an integrated, ecosystem-based, profitable, socially equitable and accepted cultivation of marine species. Research to date indicates that the divergence between possible financial returns at the level of the entrepreneurial unit and economic returns at the macro level inhibits the uptake of IMTA. It may be argued that this needs to be a key target of governance development. When the indications are that laws, rules and norms are missing or inappropriate, the lack of governance analysis is at the core of the hitherto weak engagement with IMTA. Site selection, licensing, and regulation decisions have been found arbitrary and significantly affected by politics and local leaders. Governance decisions such as subsidies, implementation, and licensing are often focused on single species, a revision of governance approaches here may turn out to be critical to the broader adoption of the growing number of successful IMTA pilots into commercial practice. Transdisciplinary and actionable knowledge on governance is needed to support governments in responding to the aforementioned challenges with incentives that facilitate implementation and reward the wider sustainability effects of IMTA operations.

Funding: This research received no external funding and the Article Processing Charge (APCs) was funded by the Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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