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Review on Integrated Multi-Trophic Aquaculture System (IMTA)

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Abstract
Aquaculture has been one of the greatest contributors to global food security in recent years. Since the past decade, aquaculture has supplied over half of the fish consumed globally (FAO, 2016) [7]. Aquaculture is expanding rapidly, particularly in regions such as Africa, Asia, Latin America, and the Caribbean, where population growth is on the rise. With increasing productivity, there is a growing demand for professionals skilled in integrated multi-trophic aquaculture (IMTA). This approach involves cultivating multiple aquatic species from various trophic levels within a single system to enhance efficiency, minimize waste, and provide ecosystem benefits similar to bio-remediation. IMTA has become a significant focus of global research due to its potential to enhance profitability and sustainability across freshwater, brackish, and marine environments. This method integrates fed species with both organic and inorganic extractive species, which utilize waste byproducts to support their growth. IMTA is recognized for its simplicity and adaptability, making it a practical solution for sustainable aquaculture. IMTA systems can be land-based or open-water systems such as marine or freshwater systems, and may comprise several species combinations (Neori *et al.*, 2004) [9]. Some IMTA systems have included such combinations as shellfish/shrimp, fish/seaweed/shellfish, fish/shrimp and seaweed/shrimp (Troell *et al.*, (2003) [14]. The combination of fish/seaweed/shellfish is very important for IMTA because this combination is cover all trophic level of water bodies.

Keywords: Integrated Multi-Trophic Aquaculture System (IMTA), fish, shellfish, seaweed

Introduction

Integrated Multi-Trophic Aquaculture (IMTA) is a sustainable approach where waste and byproducts from one aquatic species serve as resources, such as food or fertilizer, for another. This method promotes environmental balance, economic viability, and social acceptance by integrating different types of aquaculture. It combines feed-based species like fish and shrimp with inorganic extractive species like seaweed and organic extractive species like shellfish, creating a more efficient and eco-friendly system.IMTA is a sustainable aquaculture method that achieves ecological balance by selecting appropriate species and scaling their populations to provide essential ecosystem services. This approach benefits both the farmed organisms and the surrounding environment. Ideally, the co-cultured species should also generate profitable yields while enhancing total output.

With the world facing the challenge of feeding over 9 billion people in the future amid climate change, economic instability, and increasing competition for natural resources sustainable food production is more critical than ever. Currently, over a billion people suffer from malnutrition, and in aquaculture, nearly 50% of formulated feed goes to waste. This highlights the need to diversify both farming systems and species to ensure long-term food security and economic resilience.

IMTA integrates different species in a way that optimizes resource use. Fed species, such as fish and shrimp, coexist with extractive species that utilize organic and inorganic waste, such as shellfish and seaweed. By capturing and repurposing uneaten feed, waste, and nutrients, IMTA transforms by-products into valuable resources, reducing eutrophication and enhancing sustainability. The core principle of IMTA follows the idea that "the solution to nitrification is not dilution, but extraction and conversion through diversification".

For IMTA to function efficiently, careful species selection and placement are essential. The system is designed to capture waste as effectively as possible. Fed species consume food and release waste, which is then absorbed by extractive species, creating a balanced and self-sustaining ecosystem. The species involved should not only contribute to environmental sustainability but also be commercially viable, ensuring economic benefits for farmers.

Comparison with Polyculture

IMTA shares similarities with polyculture which involves cultivating multiple species together. However, IMTA is specifically structured to integrate species from different trophic levels, maximizing waste reduction and ecosystem services like bioremediation. Lower trophic-level species, such as plants and invertebrates, utilize waste products from higher trophic-level species, like finfish, to grow. These lower-trophic species can then be harvested for additional revenue or even used as feed for the higher-trophic species, creating a closed-loop system.

Global research has focused on IMTA as a promising approach to making aquaculture more sustainable and profitable in both marine and land-based systems. A common criticism of traditional finfish net pen aquaculture is that uneaten feed and waste accumulate under the pens, leading to pollution and excessive nutrient release, which can cause harmful algal blooms. However, in IMTA systems, species like seaweed or shellfish are cultivated nearby to absorb these excess nutrients, mitigating environmental impact.

IMTA in Practice

For instance, a trial conducted in Canada by Cooke Aquaculture demonstrated how kelp grown near salmon net pens effectively absorbed nitrogenous waste released by the fish. This kind of integration supports environmental health while creating additional marketable products.

IMTA systems offer multiple benefits by leveraging species interactions to enhance economic stability, environmental sustainability, and social acceptability. By incorporating fed aquaculture (e.g., finfish or shrimp) with extractive aquaculture (e.g., seaweeds and shellfish), IMTA fosters:

- Environmental sustainability through biomitigative services that maintain ecosystem balance.
- Economic stability by diversifying products, increasing overall output, and reducing costs.
- Social benefits such as job creation, improved regulatory practices, and better public acceptance of aquaculture.

By engineering aquaculture systems that mimic natural food webs, IMTA represents a viable solution for producing food in a way that supports both the environment and the economy.

Definition

IMTA is an advanced aquaculture method that involves cultivating species with complementary ecological roles at different trophic levels. This system enhances synergy between species by allowing waste, nutrients, and byproducts from one species to be captured and converted into valuable resources such as fertilizers, feed, and additional crops. Unlike polyculture, which simply involves raising multiple species together, IMTA is specifically designed to optimize resource use and ecosystem balance.

Principle of IMTA

The fundamental principle of Integrated Multi-Trophic Aquaculture (IMTA) is based on "extraction and conversion through diversification". This approach focuses on repurposing by-products and uneaten feed from fed species into valuable, harvestable crops. By efficiently utilizing waste materials, IMTA minimizes eutrophication, enhances resource efficiency, and promotes both economic and environmental sustainability. Additionally, the system supports economic diversification by integrating multiple commercially viable species, making aquaculture more resilient and profitable.

Role of Economic Analysis in (IMTA)

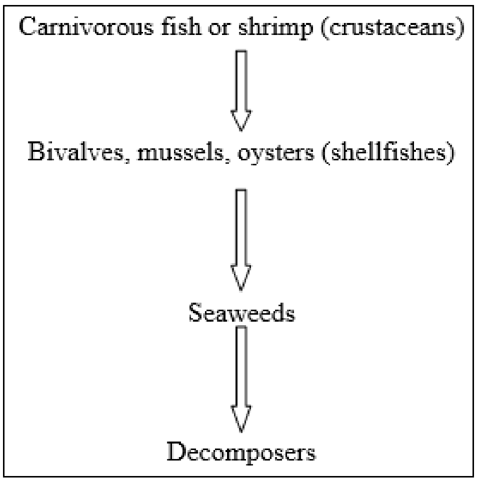
Only a few studies have undertaken a complete economic analysis of an IMTA production system, including taking account of external costs and benefits. For example, Chopin *et al*. (2001) [3]. Valued the external cost of nutrient discharge associated with salmon monoculture, using information from a technical and economic cost-benefit analysis (CBA) of a land-based salmon-seaweed farm in Chile (Alvarado,1996)[1]. The authors used solid and dissolved waste loads and the cost of waste treatment to value the external cost of nutrient discharge from the farm (Folke *et al*. (1994) [6], Buschmann *et al*. (1996) [2] and Chopin *et al*. (2001) [3] estimated the annual environmental cost of 250 tonnes of gross fish production to be USD 201 441, decreasing to USD 64 000 when an IMTA configuration was adopted to internalize this environmental cost. Later work by Chopin (2011) [5], Rose *et al*. (2014) [11], and Kambey and Chung (2016) [8] was used to value nitrogen removal in a mix of possible land-based IMTA systems considering abalone, finfish, seaweed and sea cucumbers. Kambey and Chung (2016) [8] used a STELLA model to generate physical values and a hypothetical nutrient trading credit (NTC) approach to assess the economic benefits from production and biomitigation; however, the methodology used is unclear and consolidated economic results for entire systems are not reported. Several studies have valued the external environmental costs and benefits associated with conventional and improved aquaculture practices in China. Zheng *et al*. (2009) [15]. Conducted a CBA of mariculture in Sanggou Bay, China, that analysed aquaculture operations producing extractive species. They considered how these operations affected four ecosystem services: Food production, oxygen production, climate regulation and waste treatment. Using a standard CBA approach, the authors found largely positive impacts from mariculture in Sanggou Bay on ecosystem services and social benefits. An additional assessment showed significantly higher economic and environmental sustainability for IMTA than for the major two monoculture models in the same region (Shi *et al*. 2013) [12]. The study favoured the application of IMTA in the open-water systems in China on economic grounds. Researchers have applied economic analysis to IMTA systems outside of China as well. Nobre *et al*. (2010) [10]. Applied the Drivers-Pressure-State-Impact-Response (DPSIR) approach, in comparing an abalone monoculture system to an abalone-seaweed IMTA system from both an ecological system.

System Design

To effectively capture and utilize both particulate and dissolved waste generated by fish farms, careful selection, arrangement, and placement of various components and species within the system are essential. The system's design and species selection should aim to maximize waste recapture. In marine environments, bottom-dwelling organisms such as sea urchins and sea cucumbers help process larger organic waste, including uneaten feed and fish feces that settle beneath the cages. Meanwhile, filter feeders like oysters, mussels, and scallops remove fine suspended particulate matter from the water column. Additionally, seaweeds are strategically positioned in the direction of water flow, slightly farther from the main site, where they absorb dissolved inorganic nutrients such as nitrogen and phosphate, contributing to improved water quality. The species raised in IMTA should be commercially viable as aquaculture products and grown at densities that maximize waste material absorption and use throughout the production cycle (Sasikumar G and Viji CS, (2015) [13]. IMTA involves culturing fed aquaculture species (e.g., finfish and shrimp) with extractive species that utilize the organic (from shellfish and herbivorous fish) and inorganic (from seaweed) wastes from the system for their growth, and this creates a balance between systems environmental sustainability (bio mitigation), social acceptability with better management practices, and economic stability that provides product diversification and risk reduction.

IMTA systems are designed to efficiently recapture and utilize waste products generated within aquaculture environments. As larger organic particles, such as uneaten feed and feces, settle beneath the cage system, deposit-feeding organisms like sea cucumbers and sea urchins consume them. Meanwhile, filter-feeding species such as mussels, oysters, and scallops remove fine suspended particles from the water column, enhancing water quality. Seaweeds are strategically positioned further downstream in the direction of water flow, where they absorb dissolved inorganic nutrients, including nitrogen and phosphorus, thereby contributing to bio-remediation. Organic extractive aquaculture species consume uneaten food, releasing gases that are subsequently utilized by inorganic extractive species, forming a balanced and sustainable IMTA system. For IMTA to be effective, selected species should not only contribute to environmental sustainability but also be economically viable as aquaculture products. Additionally, they should be cultivated at optimal densities to maximize waste utilization throughout the production cycle.

Nutrient Flow



Criteria for selection of fish

- Adaptation to tropical.
- Acceptance to all types of feed like natural and artificial
- High market.
- Compatibility.
- Amiability to live.

Selection of Species

Choosing species for an Integrated Multi-Trophic Aquaculture (IMTA) system requires careful consideration of their ecological functions, adaptability, and economic value.

- **Ecological Role and Waste Utilization:** Species should interact beneficially within the system, with some capable of consuming the waste produced by others.
- **Habitat Adaptability:** Preference should be given to native species that naturally thrive within their geographic range and can be cultivated using available aquaculture technologies.
- **Environmental and Technological Suitability:** The selection process should factor in particulate organic matter, dissolved inorganic nutrients, and particle size distribution to match site conditions.
- **Effective Bio-Mitigation:** Species should be able to grow to a substantial biomass to ensure continuous and efficient nutrient absorption.
- **Economic Viability and Market Demand:** Selected species should have either an established or emerging market value, whether as raw materials or processed products.
- **Potential for Commercialization:** Species that are supported by regulatory frameworks and policymakers should be prioritized to encourage market expansion.
- **Environmental and Social Sustainability:** The chosen species should contribute to improved environmental performance and align with social and political considerations.

Since environmental sustainability is a core principle of IMTA, species selection should mimic natural ecosystems, promoting both ecological balance and long-term economic success.

The co-cultured species should be more than just “bio filters”; they should also be harvestable crops of commercial value (Chopin, 2006) [3]. Fed organisms, such as carnivorous fish and shrimp are nourished by feed, comprising of pellets or trash fish. Extractive organisms, extract their nourishment from the environment (Organic and Inorganic). The two economically important cultured groups that fall into this category are bivalves and seaweed. IMTA systems have included such combinations as shellfish/shrimp, fish/seaweed /shellfish, fish/shrimp and seaweed/shrimp.

Finfish serve as the primary fed component in most Integrated Multi-Trophic Aquaculture (IMTA) systems, acting as the only source of externally provided nutrient energy. These fish contribute both dissolved and particulate nutrients to the system, along with oxidation-reduction potential-reducing compounds. Additionally, they generate revenue, making them a crucial economic factor in the industry. The quantity and composition of these nutrients depend on various factors, including the fish species, size, and feed formulation. IMTA systems can be categorized as either open (cage-based) or semi-closed (recirculating aquaculture systems). In open systems, the surrounding environment naturally supports the cultivation of extractive species. In contrast, semi-closed systems require more precise management to maintain balance between different trophic levels. Fish species selection varies between open and semi-closed systems to maximize efficiency and profitability. Some common species used in IMTA systems include *Salmo*, *Oncorhynchus*, *Scophthalmus, Dicentrarchus, Gadus, Anoplopoma, Hippoglossus, Melanogrammus, Paralichthys, and Pseudopleuronectes.*

Advantages

- **Natural Crop Insurance Alternative:** Diversifying products can help safeguard finances and minimize economic risks associated with price fluctuations.
- **Disease Prevention:** Certain seaweeds possess antibacterial properties that can help prevent diseases in farmed fish by combating harmful bacteria.
- **Higher Profitability Through Premium Pricing:** Integrated Multi-Trophic Aquaculture (IMTA) products may qualify for eco-labels or organic certifications, enabling them to be sold at higher prices.

Disadvantages

- **Requires Effective Management:** Proper oversight is necessary to regulate inputs and maintain nutrient balance.
- **Food Safety Risks:** Concerns such as parasites and coliform bacteria must be carefully addressed.
- **Lower Yield Compared to Monoculture:** Productivity levels in IMTA systems tend to be lower than those in traditional fed monoculture.
- **Species Constraints:** Not all species are compatible with IMTA systems.
- **Public Perception Challenges:** Consumer attitudes toward IMTA products may pose marketing difficulties.

Sustainability

1. IMTA enhances both economic and environmental sustainability by transforming by-products and uneaten feed from fed species into valuable harvestable crops. This process helps minimize eutrophication while promoting economic diversification.
2. By improving nutrient assimilation, IMTA reduces environmental impact and enhances the ecosystem's capacity to support cultivated species.
3. Well-managed multi-trophic aquaculture fosters accelerated growth while preventing harmful ecological side effects.
4. Economic studies indicate that IMTA can boost profitability while simultaneously mitigating financial risks.

Role in Sustainable Fish Production

- Ecologically engineer balanced systems for environmental sustainability.
- Bio-mitigative services for improved ecosystem health.
- Waste recirculation and utilization.
- Improved efficiency.
- Bio-remediation.
- Economic stability.
- Improved output.
- Lower costs.
- Product diversification.
- Risk reduction.
- Better management practices.
- Improved regulatory governance.

Conclusion

Integrated Multi Trophic Aquaculture (IMTA) combines multiple trophic subsystems, cultivating different species in close proximity while utilizing nutrient and energy transfer through water. While open-sea IMTA is a relatively new concept in India, various studies have explored the benefits of polyculture in marine aquaculture. There is significant potential for using marine macro algae as biofilters, not only to improve water quality but also to develop commercially valuable products. In 2013, global aquaculture yielded 26.9 million tons (wet weight) of aquatic plants, whereas capture production accounted for only 1.3 million tons. China and Indonesia were the leading producers. Instead of relying solely on monoculture, integrating a portion of seaweed aquaculture with fed-aquaculture can enhance sustainability by functioning as a natural filtration system. This approach could become commercially viable if high-value seaweed species are cultivated for human consumption and other applications. While financial aspects dominate existing IMTA research, they represent only part of the broader picture. To fully understand IMTA's value, further economic studies must incorporate both its positive and negative externalities, highlighting the long-term environmental and societal benefits it offers over traditional monoculture systems.

Conflict of Interest

Not available

Financial Support

Not available

Reference

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