Integrated multi-trophic aquaculture systems: A solution for sustainability

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Marine aquaculture is increasingly seen as an alternative to fishing to provide a growing human population with high-quality protein. Capture fisheries output is falling short of world demand, and annual consumption of seafood has been rising and doubled over the last three decades (FAO, 2000). Aquaculture production has surpassed supplies from capture fisheries and contributed around 51% to global fish production in 2014. Over the past three decades aquaculture production increased from 6.2 million tonnes in 1983 to 73.8 million tonnes in 2014 (FAO, 2016). This achievement was possible mainly because of the commercialisation of farm produced aquatic animals such as shrimp, salmon, bivalves, tilapia and catfish. With the diminishing availability of freshwater, the expected growth of aquaculture may increasingly take place in the marine environment. The rapid growth of the aquaculture industry has already led to growing concerns over environmental impacts and conflicts with other coastal usage in Europe, North America, Australia, and Asia.

Marine aquaculture of high value species (e.g. fish in cages) is reliant on external food supplies and has a negative impact on water quality. Marine aquaculture generates high organic and nutrient loadings, mainly from feed wastage, fish excretion and faecal production. Feed wastage may range from 1 to 38%, depending on the feed type, feed practices, culture method and species and constitutes one of the most important pollution sources (Ackefors and Enell, 1990; Seymour and Bergheim, 1991). It is noteworthy that feed wastage is much higher in open-sea cage culture systems where trash fish is used as feed. Deposition of organic waste was estimated at 3 kg per m^2 per year in the vicinity of a farm and 10 kg per m^2 per year or 1.8-31.3 kg C per m^2 per year underneath (Gowen and Bradbury, 1987).

Nutrient loading due to fish farming can be considerable (Wang et al. 2012) and can negatively impact the benthic environment due to smothering and increased organic enrichment, leading to alterations in sediment chemistry with knock-on effects on benthic biodiversity. Many attempts to reduce nutrient loading surrounding fish farms have been made by improving the digestibility of fish feeds, computerised feed-management systems and such. however, such technological improvements have not yet eliminated the problem of nutrient pollution associated with fish farming (Wang et al. 2012). One solution to reducing the environmental impact of fish farming is the use of integrated multi-trophic aquaculture (IMTA).

Integrated multi-trophic aquaculture

Integrated multi-trophic aquaculture borrows a concept from nature; namely, that in the food chain, one species always finds a feeding niche in the waste generated by another species. IMTA is a practice in which the by-products (wastes) from one species are recycled to become inputs (fertilisers, food and energy) for another. IMTA can be used to potentially recycle these nutrients by cultivating additional commercially relevant organisms. These 'extractive species' are able to intercept and assimilate aquaculture-derived waste (both organic and inorganic) when cultivated alongside fed fish species (Chopin et al. 2001; Neori et al. 2004; Troell et al. 2003).

Fed aquaculture species (e.g. finfish/shrimps) are combined, in the appropriate proportions, with organic extractive aquaculture species (e.g. suspension feeders/deposit feeders/herbivorous fish) and inorganic extractive aquaculture species (e.g. seaweeds), for a balanced ecosystem management approach that takes into consideration site specificity, operational limits, and food safety guidelines and regulations. The integrated in IMTA refers to the more intensive cultivation of the different species in proximity of each other (but not necessarily right at the same location), connected by nutrient and energy transfer through water. The aim is to increase long-term sustainability and profitability per cultivation unit (not per species in isolation as is done in monoculture), as the wastes of one crop (fed animals) are converted into fertiliser, food and energy for the other crops (extractive plants and animals), which can in turn be sold on the market. The goals are to achieve environmental sustainability through biomitigation, economic stability through product diversification and risk reduction, and social acceptability through better management practices. The major aim is to increase long-term sustainability and profitability per cultivation unit.

Selection of species

Environmental sustainability is the major consideration in IMTA, therefore the criteria guiding species selection include understanding the limitations of the natural ecosystem. When establishing which species to use in an IMTA system, one must carefully consider the suitability of the species in a particular habitat/culture unit. In order to ensure successful growth and economic value, farmers should understand its compatibility and future impact on the ecosystem.

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. The two economically important cultured groups that fall into this category are bivalves and seaweed. Combinations of co-cultured species will have to be carefully selected according to a number of conditions and criteria:

1. Complementary roles with other species in the system: Use species that will complement each other on different trophic levels. For example, species must be able to feed on the waste products of others in order for the newly integrated species to improve the quality of the water and grow efficiently. Not all species can be grown together efficiently.

2. Adaptability in relation to the habitat: Native species that are well within their normal geographic range and for which technology is available can be used. This will help to prevent the risk of invasive species causing harm to the

local environment, and potentially harming other economic activities. Native species have also evolved to be well adapted to the local conditions.

3. Culture technologies and site environmental conditions: Particulate organic matter and dissolved inorganic nutrients should be both considered, as well as the size range of particles, when selecting a farm site.

4. Ability to provide both efficient and continuous bio-mitigation: Use species that are capable of growing to a significant biomass. This feature is important if the organisms are to act as a bio-filter that captures many of the excess nutrients and that can be harvested from the water. The other alternative is to have a species with a very high value, in which case lesser volumes can be grown. However, with the latter, the bio-mitigating role is reduced.

5. Market demand for the species and pricing as raw material or for their derived products: Use species that have an established or perceived market value. Farmers must be able to sell the alternative species in order to increase their economic input. Therefore, they should establish buyers in markets before investing too heavily.

6. Commercialisation potential: Use species for which regulators and policy makers will facilitate the exploration of new markets, and not impose new regulatory impediments to commercialisation.

7. Contribution to improved environmental performance.

8. Compatibility with a variety of social and political issues.

IMTA system design

An effective IMTA operation requires the selection, arrangement and placement of various components or species, so as to capture both particulate and dissolved waste materials generated by fish farms. The selected species and system design should be engineered to optimise the recapture of waste products. As larger organic particles such as uneaten feed and faeces settle below the cage system they are eaten by deposit feeders such as sea cucumbers and sea urchins. At the same time, the fine suspended particles are filtered out of the water column by filter-feeding animals such as mussels, oysters and scallops. The seaweeds are placed a little farther away from the site in the direction of water flow so they can remove some of the inorganic dissolved nutrients from the water, like nitrogen and phosphorus. IMTA species should be economically viable as aquaculture products, and cultured at densities that optimise the uptake and use of waste material throughout the production cycle. The IMTA concept is very flexible. IMTA systems can be land-based or open-water systems, marine or freshwater systems, and may comprise several species combinations (Neori et al., 2004). Some IMTA systems have included such combinations as shellfish/shrimp, fish/seaweed/shellfish, fish/shrimp and seaweed/shrimp (Troell et al., 2003).

Integrated multi-trophic aquaculture and trophic levels in aquaculture

The use of filter-feeding organisms as nutrient extractors (inorganic and organic) has proven to be a valid alternative for nutrient bioremediation. The most frequently tested organisms are molluscs, which filter organic particles and phytoplankton, and macroalgae, which have the capability of inorganic nutrient uptake (Marinho-Soriano et al. 2011).

Integrated multi-trophic aquaculture has been proposed to achieve environmental sustainability through biomitigation of aquaculture wastes that, as compared to other accompanying methods, has advantages that may include practices (Troell et al. 2009; Barrington et al. 2009). Furthermore, IMTA is the only practical remediation approach with a prospect for additional farm revenues by adding commercial crops, while all other biomitigation approaches have generally involved only additional costs to the producer (Troell et al. 2009).

One of the differences of IMTA from the traditional practice of aquatic polyculture is the incorporation of species from different trophic or nutritional levels in the same system. In traditional polyculture, organisms may all share the same biological and chemical processes, with few synergistic benefits; they may, in fact, incorporate a greater diversity, occupying several niches, as extensive cultures (low intensity, low management) within the same pond.

In the last fifteen years, the integration of seaweed with marine fish culturing has been examined and studied in Canada, Japan, Chile, New Zealand, Scotland and the USA. The integration of mussels and oysters as biofilters in fish farming has also been studied in a number of countries and significant benefits observed.

Seaweeds

The ability of macroalgae to respond to availability of anthropogenic nutrient (nitrogen and phosphorus) input makes them an efficient instrument for bioremediation. Biofiltration by plants, such as algae, is assimilative, and therefore adds to the assimilative capacity of the environment for nutrients. With heavy growth of mariculture activities along the Indian coast, integrated multitrophic approaches primarily focused on algae are becoming of increasing importance along the coast. Commercially viable and economically important seaweed species such as *Kappaphycus alvarzii, Gracilaria dura,* and *G. edulis* can be cultivated with fishes like cobia, Indian pompano, grouper, seabass and also with lobsters. Seaweeds will act as biofilters in the present IMTA system. The red algae *Gracilaria* spp. and the green algae *Ulva* spp. have also been found to be efficient biofilters. *Gracilaria* spp. have been examined for their usefulness in laboratory studies. An efficient algal-based integrated mariculture farm maintains optimal standing stocks of all the cultured organisms, considering the respective requirements of each for water and nutrients and the respective rates of excretion and uptake of the important solutes by each of them. This allows the profitable use of each of the culture modules with minimum waste in the environment.

Open-sea IMTA in India is very recent; however, various investigations have been carried out on the beneficial polyculture of the various mariculture species. Combined culture of compatible species of prawns and fishes is of considerable importance in the context of augmenting yield from the field and effective utilisation of the available ecological niches of the pond system. Finfish culture, *Etroplus suratensis,* in cages erected within the bivalve farms (racks) resulted in high survival rates and growth of the finfish in the cages.

Co-cultivation of *Gracilaria* sp. at different stocking densities with *Feneropenaeus indicus* showed nutrient removal from shrimp culture waste by the seaweed. A ratio of 3:1 was found suitable for the co-cultivation, with 600g of seaweed able to reduce 25% of ammonia, 22% of nitrate and 14% of phosphate from 200 g of shrimp waste. Polyculture of shrimp with molluscs helps in breaking down organic matter efficiently and serves as an important food source for a range of organisms and also either directly or indirectly provides shelter or creates space for associated organisms, thus increasing the species diversity of the ecosystem. Studies have shown that an individual mussel can filter between 2-5 l/h and a rope of mussels more than 90,000 l/day. The culture of mussels could thus be used in the effective removal of phytoplankton and detritus as well as to reduce the eutrophication caused by aquaculture. Along the east coast of India, the introduction of IMTA in open sea cage farming yielded 50% higher production of seaweed, *Kappaphycus alvarezii,* when integrated with finfish farming of cobia *Rachycentron canadum*.

Invertebrates

The reduction of suspended solids and microbial pollution within aquaculture can be achieved by the use of living organisms. Literature also reveals the potential capability of some invertebrates to remediate heavy metals, microbial contaminants, hydrocarbons, nutrients and persistent organic pollutants (Khoi & Fotedar 2012; Stabili et al. 2006). Filter-feeding marine macroinvertebrates filter large volumes of water for their food requirements and exert high efficiency in retaining small particles including bacteria (Stabili et al. 2010). Detritus feeder species have also been proposed as a means for recycling the particulate organic and inorganic nutrient wastes from fish cage farming (Lander et al. 2013).

In a conceptual open-water integrated culture system, filter-feeding bivalves are cultured adjacent to meshed fish cages, reducing nutrient loadings by filtering and assimilating particulate wastes (fish feed and faeces) as well as phytoplankton production stimulated by introduced dissolved nutrient wastes. Waste nutrients, rather than being lost to the local environment, as in traditional monoculture, are removed upon harvest of the cultured bivalves. With an enhanced food supply within a fish farm, there is also potential for enhancing bivalve growth and production beyond that normally expected in local waters. Therefore, integrated culture has the potential to increase the efficiency and productivity of a fish farm while reducing waste loadings and environmental impacts.

A native bivalve species must be consider to suit the local ecology, potential markets, and the need to engineer IMTA systems to accommodate them. Literature shows that 95% of particles released from aquaculture systems, fish farms, and closed recirculation systems are ~20 microns diameter (5-200 micron range), and that they will settle. There is evidence that filter-feeders are selective in extracting particles from the water column, rejecting the rest. Thus, it is important to know the particle size of wastes from an IMTA system and to choose from among the wide range of bivalves that will select the required particle size and type.

The green mussel, *Perna viridis* and oyster *Crassostrea madrasensis* that are commercially produced along Indian coast, can economically mitigate eutrophication in integrated aquaculture. Open-sea mariculture of finfishes, when integrated with raft culture of green mussels, resulted in slight, but not significant reduction in nutrients along Karnataka.

The beneficial effect of combining bivalves such as mussels, oyster and clams as bio-filters in utilising such nutrient rich aquaculture effluents has been documented in estuaries. In a tropical integrated aquaculture system, the farming of bivalves *(Crassostrea madrasensis)* along with finfish *(Etroplus suratensis)* resulted in controlling eutrophication effectively (Viji et al, 2013, 2015). The filter feeding oysters improved the clarity of the water in the farming area; thereby reducing eutrophication. The optimal co-cultivation proportion of fish to oysters reported was 1 : 0.5 in this farming system.

Benefits of IMTA

The benefits of IMTA include:

- Effluent bio-mitigation: Mitigation of effluents through the use of bio-filters which are suited to the ecological niche of the aquaculture site. This can solve a number of the environmental challenges posed by monoculture aquaculture.

- Increased profits through diversification: Increased overall economic value of an operation from the commercial by-products that are cultivated and sold. The complexity of any bio-filtration comes at a significant financial cost. To make environmentally friendly aquaculture competitive, it is necessary to generate revenue from the activity. By exploiting the extractive capacities of co-cultured lower trophic level taxa, the farm can obtain added products that can outweigh the added costs involved in constructing and operating an IMTA farm. The waste nutrients are considered a resource in integrated aquaculture not a burden, for the auxiliary culture of bio-filters.

- Improving local economy: Economic growth through employment (both direct and indirect) and product processing and distribution.

- Form of ‘natural’ crop insurance: Product diversification may offer financial protection and decrease economic risks when price fluctuations occur, or if one of the crops is lost to disease or inclement weather.

- Disease control: Prevention or reduction of disease among farmed fish can be provided by certain seaweeds due to their antibacterial activity against fish pathogenic bacteria.

- Increased profits through obtaining premium prices: Potential for differentiation of the IMTA products through eco-labelling or organic certification programmes.

Challenges of IMTA

IMTA poses a number of challenges:

- Higher investment: Integrated farming in open sea requires a higher level of technological and engineering sophistication and up-front investment.

- Difficulty in coordination: If practised by means of different operators (e.g. independent fish farmers and mussel farmers) working in concert, it would require close collaboration and coordination of management and production activities.

- Increase requirement of farming area: While aquaculture has the potential to release pressure on fish resources and IMTA has specific potential benefits for the enterprises and the environment, fish farming competes with other users for the scarce coastal and marine habitats. Stakeholder conflicts are common and range from concerns about pollution and impacts on wild fish populations to site allocation and local priorities. The challenges for expanding IMTA practice are therefore significant although it can offer a mitigation opportunity to those areas where mariculture has a poor public image and competes for space with other activities.

- Difficulty in implementation without open water leasing policies: Few countries have national aquaculture plans or well developed integrated management of coastal zones. This means that decisions on site selection, licensing and regulation are often ad hoc and highly subject to political pressures and local priorities. Moreover, as congestion in the coastal zone increases, many mariculture sites are threatened by urban and industrial pollution and accidental damage.

Prospects

There are few doubts that IMTA is still in its infancy but presents great prospects towards becoming the aquaculture of the future, with increase production and product diversity, and also with increased quality, promoting environmental, economic and social sustainability. The use of these bioremediation organisms in co-culture with high-valued fish or shrimp species can reduce water exchange frequency and discharge of effluents as well as decrease the probability of disease occurrence in a symbiosis of environment and economic benefits – as reducing the costs in the treatment of effluent while producing biomass without spending in commercial feed is of great economic advantage.

There is tremendous opportunity to use marine macroalgae as bio-filters and to produce products of commercial value. The prospects for IMTA to become the aquaculture of the future are bright, with increased production and product diversity, increased quality, and through the promotion of environmental, economic and social sustainability.

Great opportunities come along with great challenges, and pinpointing the most suitable species to be combined in IMTA systems together with the need to create models to better assess the densities and conditions for co-culture to generate optimum revenue will require considerable research.

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