Integrated Multi-Trophic Aquaculture Systems (IMTA)

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Introduction

The aquaculture production has grown steadily owing to the dramatic expansion in this sector worldwide. During the past three decades production increased from 6.2 million t in 1983 to 70.2 million t in 2013 (FAO, 2015). Aquaculture surpassed the supplies from the capture fisheries and contributed nearly 51% to the global fish production in 2013. This achievement was possible mainly because of the commercialisation of farm-produced aquatic groups such as the shrimps, salmon, bivalves, tilapia and catfish. This sector also benefitted from the significant production of certain low-value freshwater species through integrated farming, intended for domestic production. This growth in marine aquaculture industry, has introduced many apprehensions about the environmental impacts from aquaculture waste. Intensive finfish farming in cages can release significant quantities of nutrients to the farm site, from uneaten feed, faeces and excretory products. These metabolic wastes from farm effluents, mostly ammonia, may contribute to increased nutrients and localised eutrophication in the farm. One of the major challenges for the sustainable development of aquaculture industry is to minimise environmental degradation concurrently with its expansion. Though majority of aquaculture production originate from extensive and semi-intensive farming systems, the recent increase in intensive farming of marine carnivorous fed-species is associated with environmental concerns. Integrating waste generating (fed) and cleaning (extractive) organisms in mariculture is a practical technology for sustainable mariculture. In a balanced integrated system, aquaculture effluents can be converted into commercial crops while restoring water quality.

Concept of Integrated multi-trophic aquaculture (IMTA)

Integrated aquaculture systems as detailed in Neori *et al*., (2004) Barrington *et al*. (2009) and Angel and Freeman (2009) and case studies in India are briefly given below.

In many monoculture farming systems the fed-aquaculture species and the organic/ inorganic extractive aquaculture species (bivalves, herbivorous fishes and aquatic plants) are independently farmed in different geographical locations, resulting in pronounced shift in the environmental processes. Integrated multi-trophic aquaculture (IMTA) involves cultivating fed species with extractive species that utilize the inorganic and organic wastes from aquaculture for their growth. According to Barrington (2009), IMTA is the practice which combines, in the appropriate proportions, the cultivation of fed aquaculture species (e.g. finfish/shrimp) with organic extractive aquaculture species (e.g. shellfish/herbivorous fish) and inorganic extractive aquaculture species (e.g. seaweed) to create balanced systems for environmental sustainability (biomitigation) economic stability (product diversification and risk reduction) and social acceptability (better management practices).This farming method is different from finfish "polyculture", where the fishes share the same biological and chemical processes which could potentially lead to shift in ecosystem. *Multi-trophic* refers to the combination of species from different trophic levels in the same system. The multi-trophic sub-systems are integrated in IMTA that refers to the more intensive cultivation of the different species in proximity of each other, linked by nutrient and energy transfer through water.

Selection of species

Environmental sustainability is the major consideration in IMTA, therefore the criteria guiding species selection is the imitation of natural 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:

- **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 other species' waste 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.
- **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.
- **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.
- **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.
- **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.
- **Commercialization potential**: Use species, for which regulators and policy makers will facilitate the exploration of new markets, not impose new regulatory impediments to commercialization.
- Contribution to improved environmental performance.
- Compatibility with a variety of social and political issues.

Inorganic extractive sub-system in IMTA

Bio-filtration by aquatic plants, is assimilative, and therefore adds to the assimilative capacity of the environment for nutrients. With solar energy and the excess nutrients (particularly C, N and P), plants photosynthesize new biomass. The operation recreates in the culture system a mini-ecosystem, wherein, if properly balanced, plant autotrophy counters fish and microbial heterotrophy, not only with respect to nutrients but also with respect to oxygen, pH and CO_2. Plant bio-filters can thus, in one step, greatly reduce the overall environmental impact of fish culture and stabilize the culture environment. Furthermore, farming of species that are low in food chain and that extract their nourishment from the water involves relatively low input.

Seaweeds are most suitable for bio-filtration because they probably have the highest productivity of all plants and can be economically cultured. Seaweeds have a large market for human consumption as phycocolloids, feed supplements, agrichemicals, nutraceuticals and pharmaceuticals. Seaweed farming has long been promoted in China in areas of marine cage culture for bio-extraction of nutrients in the seawater. FAO aquaculture statistics record 37 separate seaweed species groups with dominance of *Eucheuma* seaweeds (8.44 million tonnes) *Kappaphycus alvarezii* and *Eucheuma* spp. farmed in tropical and subtropical seawater followed by Japanese kelp (5.94 million tonnes).

The choice of seaweed species for inclusion in an integrated aquaculture system must first depend upon meeting a number of basic criteria such as high growth rate and tissue nitrogen concentration; ease of cultivation and control of life cycle; resistance to epiphytes and disease-causing organisms; and a match between the ecophysiological characteristics and the growth environment. In addition, given the ecological damage that may result from the introduction of non-native organisms, the seaweed should be a local species. Beyond these basic criteria, the choice of seaweed will be influenced by the intended application. If, the focus is placed on the value of the biomass produced, then subsequent decisions will be based on the quality of the tissue and added value secondary compounds. If the principal focus is the process of bioremediation, then nutrient uptake and storage and growth are the primary determinants. The optimal system would include a seaweed species that incorporates both value and bioremediation.

Among seaweeds, the ‘thin sheet’ morphology has a higher growth rate than the fleshy seaweeds. It is more difficult to generalize on nutrient sequestration. A bio-filter seaweed species must grow very well in high nutrient concentrations, especially ammonium. Seaweed that does not show this capacity has only a limited use. To take up nitrogen at a high rate, fast-growing seaweed should be able to build up a large biomass N content. The common bio-filter seaweeds, when grown in eutrophic waters, accumulate a high total internal N content. When expressed on a percent dry weight basis, maximal values for *Ulva*, *Gracilaria* and *Porphyra* grown in the eutrophic conditions characteristic of fish farm effluent range between 5–7% as N in dry weight (dw) or 30–45% as protein in dw. In addition to the requisites described above, the ideal choice for the seaweed bio-filter also has a market value. This encompasses the sale of seaweed products for a range of markets, including human consumption as food or therapeutants, specialty biochemicals, or simply as feed for the algivore component of the integrated system.

Only a handful of seaweeds have been thoroughly investigated for their aquaculture and/or bioremediation potential. Perhaps the most complete body of research has encompassed the genus Ulva. These flat sheet morphotypes have correspondingly high growth rates as well as high nitrogen contents, making them very good candidates for remediation. Their life cycle and its controls are generally well known, and *Ulva* has been successfully integrated into mid-to large-scale animal mariculture systems. Possibly the only drawback is the limited market for harvested biomass. *Gracilaria* has a history of mariculture study, whereas Kelps (*Laminaria*) and *Porphyra* cultivations are thought to have a potential for generating a viable seaweed mariculture and integrated aquaculture.

Along Indian coast *Kappaphycus alvarezii* were used in IMTA and has emerged as a promising species in open sea integrated aquaculture.

In open mariculture systems, nutrient uptake efficiency by seaweeds has been low in some systems due to the 3-D hydrographic nature of the water flow; this technology therefore requires further R&D and modelling (such as on the potential of several harvests of several crops). Furthermore, studies investigating the open-water integrated mariculture approach have been hampered by the difficulties involved with experimentation and data collection at sea.

Organic extractive species sub-system in IMTA

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 any 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.

How filter-feeders interact with the environment, their uptake rate, and other aspects are available in the literature. 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.

Marketability of these secondary products is a factor, but it need not be an overriding consideration. You could add a fish range alongside your primary fed fish to act as a first-stage bio-filter and use a marine bivalve as the second stage. An example of an ecosystem-based IMTA model was built as a Peace Corps-style project in Malaysia in the 1990s to remove contaminants from shrimp farm waste water, otherwise normally released into local waters. The project found that 72% of the nitrogen and 61% of the phosphorus could be removed, mostly as harvested shellfish product using a simple, engineered system.

Studies have shown that bivalves are capable of utilising fish farm wastes as an additional food supply. However, few practical studies have been undertaken, with conflicting conclusions regarding the potential for open-water integrated culture to enhance bivalve production and, by implication, to significantly reduce fish farmwastes.

The bivalve mussel, *Perna viridis* and oyster *Crassostrea madrasensis* that are commercially produced along Indian coast, can economically mitigate eutrophication in integrated aquaculture.

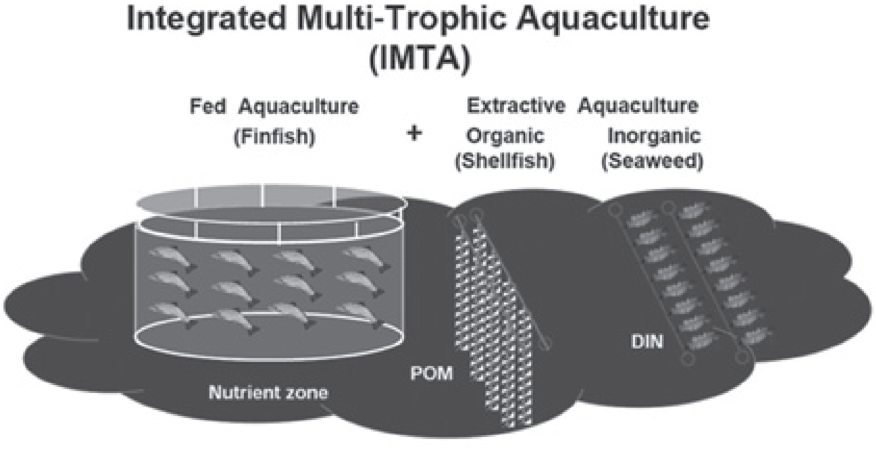
Fed-aquaculture species sub-system in IMTA

Finfish represent the only fed component of most IMTA systems and thus represent the only human provided input of nutrient energy to the system. In their role within an IMTA system, fish provide dissolved and particulate nutrients and oxidation reduction potential reducing compounds to the other component organisms as well as revenue to the industry. The quantity and form of these nutrients is dependent on species, size and feed formulation among other factors.

Feed formulation provides perhaps the most obvious route for fish effluent modification for the extractive components, conversely, other trends in the aquafeeds industry may impact fish effluent quality for an IMTA system. There is a distinction between IMTA systems that are open to the environment (cage based) and semi-closed to the environment (recirculation aquaculture systems). In most open systems the environment is both necessary and sufficient to rear extractive organisms, while in contrast the semi-closed systems require much tighter coupling of the different trophic levels under cultivation. Fish species selection for open and closed systems would likely differ to take advantage of each systems' unique characteristics in order for the industry to be profitable.

IMTA system designs: 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 optimize 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, like sea cucumbers and sea urchins. At the same time, the fine suspended particles are filtered out of the water column by filter-feeding animals like 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

Conceptual diagram of an integrated multi-trophic aquaculture (IMTA) operation combining fed aquaculture (finfish) with organic extractive aquaculture (shellfish), taking advantage of the enrichment in particulate organic matter (POM), and inorganic extractive aquaculture (seaweeds), taking advantage of the enrichment in dissolved inorganic nutrients (DIN)



Source: Chopin (2006).

inorganic dissolved nutrients from the water, like nitrogen and phosphorus. IMTA species should be economically viable as aquaculture products, and cultured at densities that optimize the uptake and use of waste material throughout the production cycle.

Case studies

In temperate waters Canada, Chile, China, Ireland, South Africa, the United Kingdom of Great Britain and Northern Ireland (mostly Scotland) and the United States of America are the only countries to have IMTA systems near commercial scale. France, Portugal and Spain have ongoing research projects related to the development of IMTA. The countries of Scandinavia, especially Norway, have made some individual groundwork towards the development of IMTA, despite possessing a large finfish aquaculture network (Barrington *et al*. 2009).

Studies have focussed on the integration of seaweeds with marine fish culturing for the past fifteen years in Canada, Japan, Chile, New Zealand, Scotland and the USA. The integration of mussels and oysters as bio-filters in fish farming has also been studied in a number of countries, including Australia, USA, Canada, France, Chile, and Spain. Recent IMTA research includes a focus on seaweeds, bivalves and crustaceans. Studies conducted in an IMTA systems incorporating *Gracilaria lemaneiformis* and *Chlamys farreri* in North China have shown that a bivalve/seaweed biomass ratio from 1:0.33 to 1:0.80 was preferable for efficient nutrient uptake and for maintaining lower nutrient levels. Results indicate that *G. lemaneiformis* can efficiently absorb the ammonium and phosphorus from scallop excretion.

In China, Seaweeds, *Gracilaria lemaneiformis*, grown over 5 km of culture ropes near fish net pens on rafts increased the density from 11.16 to 2025 g/m in a 3-month growing period. The scaling up of culture area during the following 4 months to 80 km of rope, reported an increase in culture density on ropes to 4250 g/m. An increase in the biomass of *Gracilaria* (in the culture area) to 340 t wet weight was estimated due to its culture in close proximity to fish net pens. Different work along similar principles has taken place elsewhere.

Studies on IMTA have been carried on the East coast of Canada, where Atlantic salmon (*Salmo salar*), kelp (*Saccharina latissima* and *Alaria esculenta*) and blue mussel (*Mytilus edulis*) were reared together at several IMTA sites in the Bay of Fundy. The study has shown that the growth rates of kelp and mussels cultured in proximity to fish farms have been 46 and 50% higher, respectively, than at control sites. Several other studies have also reflected on the faster growth of mussels and oysters grown adjacent to fish cages. This reflects increase in nutrients and food availability from the finfish cages. Taste tests of mussels grown in conventional aquaculture and mussels grown at these IMTA sites showed no discernible difference; meat yield in the IMTA mussels was, however, higher. Findings of the economic models have also shown that increased overall net productivity of a given IMTA site can lead to increased profitability of the farm compared with monoculture.

Studies from land-based systems indicated that seaweeds can remove between 35% and 100% of dissolved nitrogen produced by fed species. The capacity of seaweeds in open-water cultures to remove nutrients from the water column can be estimated based upon the fraction of available nutrients, which are bound by the seaweeds at any given point in time. Experimental data and mass balance calculations indicated that a large area of seaweed cultivation, up to one ha for each ton of fish standing stock, would be required for the full removal of the excess nitrogen associated with a commercial fish farm.

The 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. The ratio of 3:1 was found suitable for the co-cultivation. The seaweed (600 g) was able to reduce 25% of ammonia, 22% of nitrate and 14% of phosphate from the shrimp (200 g) 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 organism, 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 mussel more than 90000 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 *Rachycentron canadum*.

Open-sea mariculture of finfishes when integrated with raft culture of green mussels, *P. viridis* 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 utilizing 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:

- **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 raise its revenues. 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 in integrated aquaculture not a burden but a resource, 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:

- **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 is tremendous opportunity to use marine macroalgae as bio-filters, process and produce products of commercial value. Globally, most open-water seaweed monoculture has taken place in Asia, South America, South Africa and East Africa. In 2013, 26.9 million tonnes (wet weight) of aquatic plants from aquaculture was harvested worldwide, while capture production was only 1.3 million tonnes, with China and Indonesia accounting for the major share in production. Instead of monoculture, a fraction of the seaweed aquaculture practice can be integrated with fed-aquaculture as bio-filters. This approach may generate a heightened commercial interest once high value seaweeds species can be cultured as biofilters that produce novel human food products.

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