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Biodynamics in tropical integrated aquaculture systems and challenges in producing organic food using low-carbon methods

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Abstract

Biodynamics of water quality and related issues in integrated aquatic farming systems, especially the Integrated Multi-Trophic Aquaculture (IMTA), are reviewed in this paper. Combining several species in one system in addition to the microbiological organisms that become part of a production unit achieve biodynamics that is truly remarkable and mimics the processes that nature utilizes through biodiversity and interlinkages. Nutrient cascading is the most visible process in such a system. Some of the features that characterize IMTA include: harmonious functioning of multiple species, self-manuring, in tune with nature, wellbeing of captive stocks and low-carbon processes. Basically, IMTA has three loops: fed species and biofiltration, and the water quality impacted by processes in the first two loops. Maintaining homoeostasis in the system can be challenging for a number of reasons, including species-specific water quality requirements, turnover of dissolved gases (mainly oxygen and nitrogen) and particulate matter. Ammonia fluctuates with pH and temperature. Dissolved oxygen is influenced by temperature. While at neutral pH (7.0), more than 95% of ammonia is in ionized, non-toxic form (NH_4^+), the percentage of toxic un-ionized ammonia (NH_3) increases with pH at a given temperature. NH_3 is highly toxic. It produces stress at 0.1 mg/L by damaging the gills and disrupting metabolism, and death at higher concentrations. Nitrite is toxic when its concentration exceeds 0.4 mg/L. Concentration lower than this value can be fatal for more sensitive species. Process of nitrification that converts ammonia to nitrite and nitrite to nitrate requires at least 6 mg/L of dissolved oxygen. The culture system should remain well aerated, at slightly alkaline pH and moderately warm temperature, and must have substrate for nitrifying bacteria. Roles of the various types of filtering devices for organic and inorganic wastes are discussed in this paper.

Keywords: Nature-inspired, IMTA systems, Biodynamics, Biofiltration, Organic food

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Introduction

There is a growing interest in Integrated Multi-Trophic Aquaculture (IMTA) because of its several attributes that include: recycling of waste for biomass gain, reducing ecological footprint, increasing production efficiency per unit area, low input costs, and making multiple types of high-quality food available in restricted spaces even in hinterland regions with limited provisions and services. Because food production amounts to one-third of greenhouse emissions globally, IMTA provides an option to reduce the carbon footprint through several interrelated biodynamic processes. IMTA represents a model of biodynamics that demonstrates how the scientific knowledge can be integrated with the processes that occur in nature. It is a holistic, ecological and ethical approach to sustainable aquaculture. The core principles and practices of biodynamics can be applied anywhere aquaculture is carried out with necessary adaptations according to scale, weather conditions and indigenous cultures.

The integration of several species in one system makes it far more biodynamic than a monoculture system as these species essentially form one production unit despite having different behaviors, physiological processes, growth patterns and other biological features (Figure 1). In fact, the compatibility of multiple species and functioning of the system as an integrated whole defines each IMTA module's individuality and living entity.

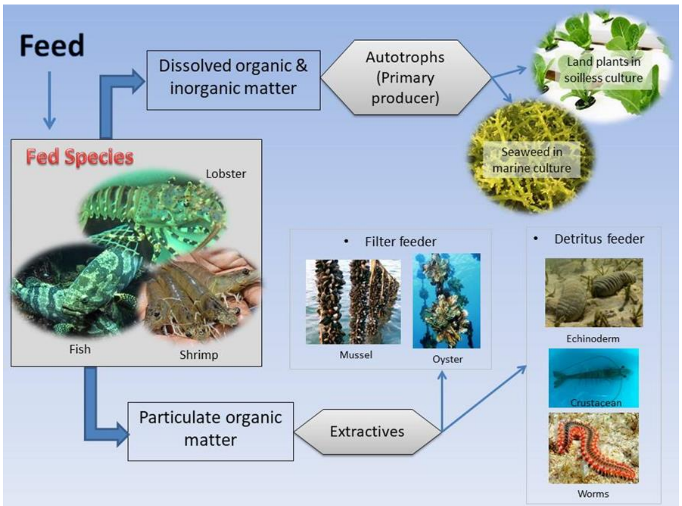

Figure 1. Fed and extractive species that can be integrated in a culture system.

Selection of species and the rate at which they are stocked have significant bearing on water quality and efficiency of organic production, and are, therefore, key factors in determining the success of IMTA.

There is a growing body of literature on IMTA. Some of the notable contributions are reviewed here. Chopin et al. (2001) and Ridler et al. (2007) elaborated the environmental compatibility of IMTA in terms of waste recycling. Hirata et al. (2007) explained the 'ecosystem homeostasis' achieved by combined stocking of seaweeds and fish. Soto and Jara (2007) emphasized the importance of using mussels for filtering the particulate matter. Shpigel and Neori (2007) demonstrated the efficiency of *Ulva lactuca* in ammonia removal from the water. Estim and Mustafa (2010) published data to show the use of Aquamat™ in improving water quality by providing a larger surface area for nitrifying bacteria. Estim (2015) reviewed important findings in this area and presented IMTA as a good example of low-carbon model of aquaculture.

Al-Azad et al. (2017) published data based on comparative assessment of nutrients in seaweed tanks with those in land-based IMTA system. Estim et al. (2017) presented information on biological and mechanical filtration in the recirculating aquaculture system. Sumbing et al. (2016) examined growth performance of spiny lobster (*Panulirus ornatus*) in a land-based IMTA. Recently, in a thought-provoking paper, Mustafa and Estim (2018) emphasized the importance of incorporating nature's design principles as far as possible for sustainable aquaculture represented by IMTA.

Operational biodynamic principles of IMTA

1. **Harmonious living entity.** A module of IMTA serves as an integrated living entity comprising many different components. These components are well harmonized, and managed in a holistic and dynamic way to support the health of the whole production unit. This is necessary to boost the resilience and production efficiency of IMTA despite the system having to deal with different organisms, intricate nutrient cascading, culture medium requirements and waste recycling.

2. **Cultivates biodiversity.** IMTA is inspired by natural aquatic ecosystem and its uniqueness. Some species are selected and introduced while others (for example, beneficial nitrifying bacteria) become a part of the system to contribute to its homoeostasis. It combines plant as well as animal species that work together unlike many conventional farms that grow crops or raise livestock separately. The module is open to additional species that can help in stability and productivity.

3. **Self-manuring.** IMTA has an inbuilt self-manuring mechanism. Wastes produced by fed species are picked up by the others organisms in the rearing system to support their biomass gains and maintain the water quality. This on-farm fertility eliminates the need for exogenous fertilizers.

4. **Holistic healthcare of stocked species**. Biodynamic systems of IMTA seek to create balanced conditions that boost the health and stamina of stocked species, enabling them to resist diseases. Of course, IMTA is not free of diseases but the underlying problem can be diagnosed and addressed. Mostly, it is linked to imbalance in some of the system components that can be rectified to bring the farming module to a better health condition.

5. **Ethical treatment of captive animals.** IMTA system is motivated by the need to meet the living requirements of the stocked animals, keep them healthy and strengthen their immune system to fight diseases. This helps the animals perform their activities in a better environment. The fed species are offered food appropriate for their digestive system to handle. They are held in a suitable stocking density so as not to impair water quality while allowing space for movement. Only those species are selected that are amenable to captivity.

6. **In tune with natural phenomena**. IMTA can be adapted in many ways and practiced under a variety of conditions- land-based or sea-based. The animals that require exposure to currents, tides, lunar rhythm, and a more vigorous flushing can be grown in facilities installed in the sea. Others, especially freshwater species such as tilapia, and plants like green beans, can be grown in land-based facilities.

7. **Creativity and perception**. There is no limit to adaptations in IMTA modules in terms of design and scale. This opens up a new frontier for application of creative ideas and innovative solutions. Selection of species, their conditions of captivity, stocking rates of individual species, suitability of the rearing medium, weather, local conditions, filter media (substrate for nitrifying bacteria required for biofiltration) are open to new trials for improvements. Besides, sustainable and profitable farming methods inspired by nature also serve to change the community perspectives in favor of environment-friendly aquaculture. Probably, this will contribute to a rapid development of blue growth and achievement of the relevant sustainable development goals. It will also spur interest in bringing climate change adaptation in aquatic food production and public awareness of the environment and issues related to sustainable development.

8. **Certification and blue label**. Seafood consumers are increasingly concerned about quality of the farmed food and also want to know if the food is produced by responsible methods. This requires improving the environmental, social and economic performance of the aquaculture supply chain to be able to earn premium price and penetrate niche markets locally and globally. There are accredited agencies for certification that check the compliance of aquaculture with the set standards and specifications. IMTA stands a better chance in organic certification. With the certificate it becomes easier to carry out global trade involving seafood. Furthermore, the aquatic food grown by responsible methods will pass the inspection randomly conducted by food quality control agencies.

Key attributes of IMTA for its biodynamics include:

1. Achieving water quality remediation by appropriate selection of extractive species.
2. Stocking one fed species and more than one extractive species.
3. Hydraulic mechanisms that enable the combination of biofiltration on a fluidized bed that detoxifies nitrogenous waste despite a daily feed intake.
4. Maintaining the water quality parameters in a permissible range through selection of species and their stocking rates.
5. Facilitating storage of chemical energy in the bonds of organic macromolecules that yield physiological fuel value on consumption of fed species (fish, lobster), organic extractives (sea cucumber) and inorganic extractives (seaweed, green bean).

In view of the above features, IMTA provides a model of aquaculture that works on the principle of 'producing something out of nothing' that obviously involves conservation of water by recirculation and recycling of waste rather than material inputs to run the operations. It functions in compliance with the first law of thermodynamics wherein energy undergoes transformations but remains preserved, and a significant part of which is utilizable as human food.

Undoubtedly, IMTA reduces the use of natural resources but a fed species depends on exogenous food supply. Environmental compatibility will not be compromised if the supplied feed comprises ingredients from sustainable sources. In the second loop of the system, the wastes generated are taken up by inorganic extractives (autotrophs) and organic extractives (heterotrophs) that include filter feeders and deposit feeders. This process can be differentiated into three loops where Loop-1 pertains to fed species, Loop-2 concerns species performing biological filtration and Loop-3 represents a critical stage where water is recycled or removed from the system, to be replaced by fresh supply. Challenges to IMTA can arise at any of these loops (Figure 2), and they need to be addressed.

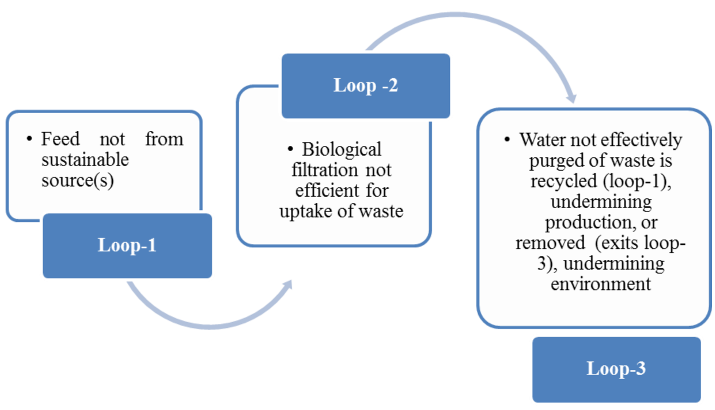

Figure 2. IMTA loops and potential challenges.

At Loop-1, the challenge is to develop a feed that comprises ingredients from sustainable sources, and is nutritionally balanced and supports growth of the fed species. Some aquaculture species are euryphagic and their anatomical and physiological capabilities enable them to adapt to a formulated diet.

Loop-2 is an active phase in terms of water quality dynamics. It handles metabolic waste of fed species and unutilized feed remains which if untreated would impair the water quality. This loop should ideally comprise more than one species, one with autotrophic mode for uptake of dissolved nutrients for primary production using solar energy (land plants grown in water) or seaweeds. If for reasons of excessive nutrients coming from Loop-1, or inability of the autotrophs to carry out effective biofiltration, then the water quality could pose risk to the production system.

In a broader sense, biofiltration covers any filtration technique that uses living organisms to remove unwanted substances from wastewater. Ammonia removal is the most important process in Loop- 2. Ammonia is the first form of nitrogen released from decay of unutilized feed residues and is the main nitrogenous waste excreted by most fish and aquatic invertebrates. It is present in two forms: un-ionized (NH_3) and ionized (NH_4^+), also known as ammonium ion. Un-ionized ammonia is highly toxic to fish whereas ionized ammonia is not until in very high concentration. These nitrifying bacteria require structures (or substrate) to colonize, and these structures are placed in the tank (Loop-2). Bacteria concentrate on the substrate, stick to each other and become embedded with a slimy extracellular matrix. It is called as 'biofilm'. In addition to biofilm filtration, IMTA comprises land plants that can adapt to growth in a soilless culture or seaweeds that can thrive in the system. By uptake of dissolved substances in the waste these stocked plants or plant-like protist (seaweeds) help in removing dissolved substances. The filter-feeding species (for example, mussels) and deposit-feeders (example, sea cucumbers) tend to remove particulate form of the waste materials. Conversion of energy into biomass happens more efficiently in seaweed that grows in water and does not need to fight gravity. This is unlike land plants where growth in response to positive phototropism follows negative gravitropism. Seaweed is buoyed by water and does not need lignin that makes wood to stand up against gravity. It has no roots, stems and leaves, and does not need vascular system (xylem and phloem) to transport water and nutrients.

Water quality profile in IMTA systems

Concentrations of dissolved gases principally determine the suitability of water for aquaculture. These gases include: Oxygen (O_2), Carbon dioxide (CO_2), Nitrogen (N_2), Ammonia (NH_4^+ and NH_3), Hydrogen sulfide (H_2S), Chlorine (Cl_2) and Methane (CH_4).

Most of the dissolved gases are not routinely measured in water quality assessment and reporting in aquaculture because the routine sampling methods might not necessarily give accurate results and may be this data will be of little practical use. Dissolved CO_2 is highly soluble in water. In aquatic habitats, including aquaculture ponds, most of the dissolved CO_2 is due to respiration. Atmospheric CO_2 also dissolves in water in a small proportion because of the low partial pressure of this gas in the air. Its level fluctuates and is inversely related to DO. At high stocking density and poor aeration, when DO declines, DCO_2 increases to a level that puts stress on the fish, mainly by interfering with the ability of fish to extract oxygen from water and creating acidity (low pH). Aeration easily drives off CO_2. H_2S is not a problem in IMTA systems. It can develop in intensively stocked ponds due to anaerobic decomposition of organic matter by the bacteria at the pond bottom. It is a toxic substance and is more harmful at higher temperature and when pH is less than 8. Oxygen readily renders it harmless.

Dissolved oxygen and nitrogen-containing gases are among those generally measured in IMTA.

Dissolved oxygen

Dissolved oxygen concentration greatly varies depending on several factors. Aquaculture animals need 4-5 mg/L of DO to avoid stress. Increase in water temperature, and rates of stocking and feeding tend to reduce the levels of DO. Tropical species of fish in Malaysia experience serious stress if DO reduces to 2 mg/L, and do not survive when DO reaches less than 1 mg/L. In in addition to regular DO monitoring it is also advisable to look for behavioral response of the fish that characterize signs of DO deficiency such as: loss of appetite, aggregation near the water inflow pipe, frequent surfacing and some form of sluggishness. Air-breathing fish will be more resilient to DO deficiency due to their ability to gulp air and extract oxygen. However, such species will increase the rate of surfacing to compensate for low DO in water. A sustained deficiency of DO will retard the growth of the fish and make it vulnerable to diseases.

Ammonia, Nitrite and Nitrate

Ammonia is highly toxic. It has to be eliminated from any aquaculture system. Special considerations are given in IMTA to prevent the build-up of this toxic substance. Ammonia is a waste product of protein metabolism. In water, it occurs in two forms: ionized (NH_4^+) and un-ionized (NH_3). Sum of these two forms is referred to as the Total Ammonia Nitrogen (TAN). NH_3 is extremely toxic to the fish but NH_4^+ is not except when its levels are very high. The ratio of NH_3 to NH_4^+ in water at any given time depends on the pH and temperature (Timmons et al., 2002). There is more NH_3 at higher temperature and higher pH. It can be determined from TAN if the water quality monitoring data includes pH and temperature measurements.

At pH 7.0 or below, most ammonia (>95%) is in non-toxic form ($NH4^+$). The percentage of toxic un-ionized ammonia (NH_3) increases with pH at a given temperature (Table 1). For example, assuming the TAN value is 4.0 at temperature of 30°C and pH 9.0, the concentration of toxic form of TAN (NH_3) would be 4.0 x 0.4453 = 1.7812 mg/L when using the ratio, not the percent. If TAN is 1 then NH_3 = 1 x 0.0502 = 0.0502 mg/L.

Table 1. NH_3 in aqueous solution at different values of pH and temperature (Emmerson et al., 1975). The amount of NH_3 in a water sample can be calculated by multiplying TAN by the factor shown in the table against the pH and temperature.

pH	Temperature, °C				
	24	26	28	30	32
7	0.0052	0.0060	0.0069	0.0080	0.0093
7.2	0.0083	0.0096	0.0110	0.0126	0.0150
7.4	0.0131	0.0150	0.0173	0.0198	0.0236
7.6	0.0206	0.0236	0.0271	0.0310	0.0369
7.8	0.0322	0.0370	0.0423	0.0482	0.0572
8.0	0.0502	0.0574	0.0654	0.0743	0.0877
8.2	0.0772	0.0880	0.0998	0.1129	0.1322
8.4	0.1171	0.1326	0.1495	0.1678	0.1948
8.6	0.1737	0.1950	0.2178	0.2422	0.2768
8.8	0.2500	0.2774	0.3062	0.3362	0.3776
9.0	0.3456	0.3783	0.4116	0.4453	0.4902
9.2	0.4557	0.4909	0.5258	0.5599	0.6038
9.4	0.5702	0.6045	0.6373	0.6685	0.7072
9.6	0.6777	0.7078	0.7358	0.7617	0.7929
9.8	0.7692	0.7933	0.8153	0.8351	0.8585
10.0	0.8408	0.8588	0.8749	0.8892	0.9058

In terms of percentage, at a temperature of 28°C and pH 8, the NH_3 amounts to 6.55% but when pH increases to 9 the NH_3 rises to 41.16%. Nitrification rate is higher in warm waters. Sajuni et al. (2010) conducted experiments in the temperature range 27–32°C and observed decline in efficiency of ammonia removal with decrease in temperature. This suggests the influence of physical and chemical factors on the dynamics of nitrification and residence of ammonia in the aquaculture system.

NH_3 is highly toxic to the fish. There are interspecific differences in ammonia tolerance in fish. Even the value 0.1 mg/L can cause significant damage to sensitive structures like gills, disrupt metabolism and curtail growth. NH_3 in concentration even as low as 0.0125 mg/L has been reported to adversely affect the condition of trout (Parker, 2002). At 0.5 mg/L NH_3 is lethal to most of the species tested.

Nitrite (NO_2^-) is an intermediate stage in the conversion of ammonia to nitrate. It is highly toxic to the fish. Even doses exceeding 0.4 mg/L can be fatal. In the presence of DO, the transformation of nitrite into nitrate happens quickly. Concentration of DO of about 6 mg/L is adequate for colonization of the bacteria and nitrification, and for reducing the possibility of toxicity due to temporary increase in the concentrations of ammonia and nitrites (Camargo et al., 2005).

In biological filtration, ammonia is converted into nitrate nitrogen in a two-step process called as nitrification: Step 1- Conversion of ammonia and ammonium to nitrite (NO_2) by *Nitrosomonas* bacteria. Step 2- Conversion of NO_2 to nitrate (NO_3) by *Nitrobacter* bacteria. These steps are shown in Figure 3. These bacteria function efficiently when DO level is at least 6 mg/L.

Ideally, ammonia should not persist in the culture tanks. It should transform as soon as produced. If this does not happen and it continues to build up, that is an indication of impairment of some regulatory controls in the system. Remedial action is immediately required under this situation. Suggested measures are decreasing the stocking density, reducing feeding or temporarily avoiding food supply, increasing aeration, flushing of waste (fecal matter and uneaten food remains) and renewal of water. A positive TAN test should be followed by analysis of actual concentration of NH_3. Concentration of TAN above 0.05 mg/L can inflict serious harm to the fish and at 2.0 mg/L fish will begin to die. Fish are not observed to consume food in the presence of ammonia, and continuing feed supply will only lead to more of uneaten food and worsening of the culture conditions.

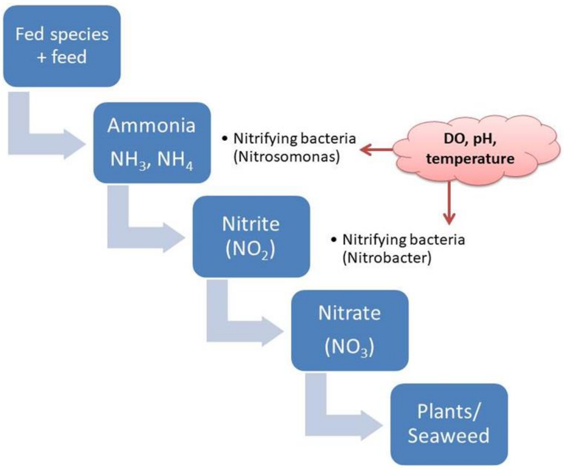

Figure 3. Schematic representation of the biofiltration process in IMTA.

Role of nitrifying bacteria deserves due importance. Their scavenging of potentially toxic nitrogenous compounds (NH_3 and NO_2^-) eventually yields the soluble nitrate (NO_3^-). These nitrogen transformations are oxidative biochemical reactions that are respiratory, utilizing oxygen by the nitrifying organisms. Decline in DO below 4.5 ppm slows down the metabolism of these bacteria. Although, not usually carried out in IMTA, the biofilm microscopy is highly recommended for these reasons. Presence of these bacteria can be presumed in IMTA system but scientific validation is needed for taking measures to prevent disruption of nitrification process or to enhance it. There are many types of filter media (made up of natural or artificial non-toxic materials) used for nitrification in recirculating aquaculture. They differ in their filtration efficiency but all provide the substrate for the nitrifying autotrophic bacteria to grow. Those with high specific surface area for bacterial colonization and low clogging properties are more effective (Hagrove et al., 1996).

A rigorous water quality monitoring that should happen in Loop-3 is, therefore, critically important. IMTA aims to achieve recyclable water quality by selecting species in Loops 1 and 2 and adjusting their stocking biomass. However, when water renewal is necessary then use of this released water is possible in land-based IMTA modules by diversion to plants, especially those grown for food harvest. The reference standard of water quality for aquaculture is presented in Table 2.

Table 2. Summary of water quality standards for aquaculture (Source: PMNQ WQ Standard).

Parameter	***Unit***	***Malaysia standard***	***Desirable value***
Freshwater aquaculture			
pH	No unit	6.5 – 9.0	6.5 – 9.0
DO	mg/L	3 - 7	>5.0
TAN	mg/L	0.3	<0.01
NO_3	mg/L	7.0	<0.5
NO_2	mg/L	0.40	
P	mg/L	0.1 – 0.2	
TSS	mg/L	25 - 150	
TDS	mg/L	500 - 1000	
Marine aquaculture			
pH	No unit	6.5 – 9.0	6.5 – 9.0
DO	mg/L	3 - 7	>5.0
TAN	mg/L	0.3	<0.01

Maintaining these parameters in the optimum range is challenging in the water recirculating system of IMTA. However, it is possible to achieve the standard values through selection of species, their appropriate stocking rates and biofiltration substrates, and by modulating the culture system.

Experimental trials involving various integrated systems

Experimental trials involving spiny lobster (*Panulirus ornatus*) in recirculating and flow-through systems show that it is easier to manage water quality in a flow-through system compared to recirculating system. It is evident from Figure 4 that a flow-through system for spiny lobster brings down all the concentrations of the nitrogen fractions until within the tolerance level of the fed species. Because water quality parameters influence survival and growth, it is important to manage them for efficient production and yield of high-value species such as the spiny lobster (Table 3).

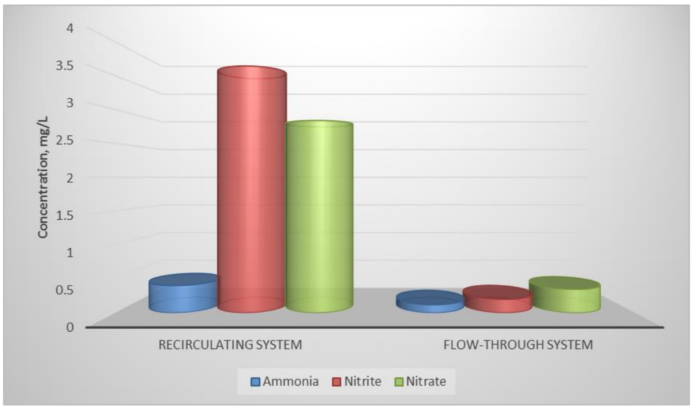

Figure 4. Concentrations of ammonia (NH_3), nitrite (NO_2) and nitrate (NO_3) in recirculating and flow-through systems used for lobster culture. Source: Sumbing et al. (2016).

Table 3. Survival and growth of spiny lobster in recirculating and flow-through culture systems. Source: Sumbing et al. (2016).

Parameters	Recirculating system	Flow-through system	Difference
Survival, %	80	93.3	P>0.05
Specific Growth Rate, %day^{-1}	0.096	0.125	P>0.05
Body weight gain (10 week trial)	9.6	13.2	P>0.05

While these differences are not statistically significant over a 10-week trial but might be significant at this rate over a longer culture period if this trend prevails, requiring readjustment of stocking density of lobster or that of inorganic and organic extractives. With the kind of biodynamics that prevails in IMTA, it is difficult to extrapolate the 10-week results into end results for one year of culture period.

Recirculation system, on the other hand, requires additional components to maintain the water quality. These can be in the form of media filters that provide habitat for nitrifying bacteria, or plants and seaweeds. Estim and Mustafa (2014) reported the use of a special geotextile material, the Aquamat, which was found to be effective in promoting biological filtration to control the nitrogenous fractions (Figure 5).

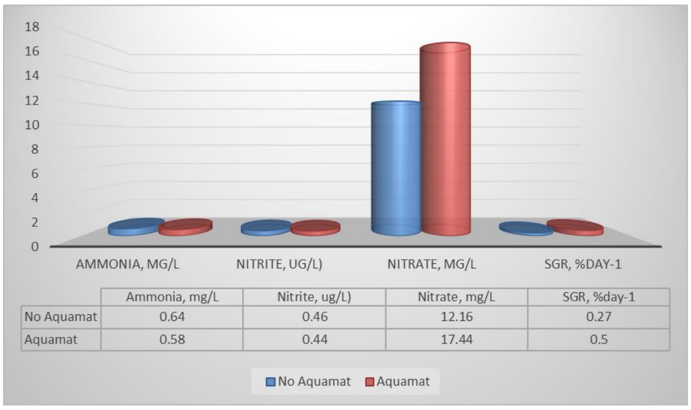

Figure 5. Nitrogenous fractions in *Epinephelus lanceolatus* tanks with and without aquamat. Source: Estim and Mustafa (2014).

Estim and Mustafa (2010) used a variety of substrates as well as seaweed to determine the efficiency of water quality remediation (Table 4).

Table 4. Ammonia, Nitrite and Nitrate concentrations (Mean ±SD) in four treatment systems. Source: Estim and Mustafa (2010).

Water quality parameters	CR	AQ+CR	SW+CR	AQ+SD W+CR
Temperature °C	25.99 ± 0.82	26.03 ± 0.85	26.05 ± 0.82	26.04 ± 0.82
DO, ppm	5.95 ± 0.24	5.64 ± 0.37	5.66 ± 0.24	5.71 ± 0.29
pH	8.11 ± 0.05	8.07 ± 0.09	8.08 ± 0.07	8.06 ± 0.09
Salinity, ppt	31.7 ± 0.4	31.1 ± 2.2	31.7 ± 0.4	31.4 ± 1.6
NH_3-N, mg/L	0.85 ± 0.76	0.31 ± 0.20	0.72 ± 0.71	0.35 ± 0.23
NO_2-N, ug/L	0.80 ± 0.21	0.55 ± 0.15	0.20 ± 0.04	0.32 ± 0.10
NO_3-N, mg/L	3.79 ± 2.58	10.24 ± 4.22 c	2.45 ± 1.22	5.06 ± 3.76

CR = Coral rubble; AQ = Aquamat; SW = Seaweed (*Eucheuma spinosum*)

The key findings of this experiment are: Nitrification occurred in all tanks, nitrification rates were significantly different (P<0.05), nitrification was more efficient in AQ + CR and AQ + SW + CR compared to the others, and efficiency of nitrification was lowest in CR compared to the others (the remaining three tanks). Effectiveness of seaweeds deserves thorough investigations not just for reasons of water quality remediation but also boosting resilience of many models of low-carbon aquaculture. Hirata et al. (2007) have documented the performance of green seaweed (*Ulva pertusa*), also known as sea lettuce, in improving growth and production of sea bream (*Pagrus major*) by 3.2% in integrated culture and outlined the significance of follow-up studies on this topic.

With more than one filtering device used in the system it becomes difficult to quantify the role of each one of them. Seaweeds are well adapted to functioning in permanent contact of their entire body surface with the seawater. They have a thin external layer of body wall that helps in uptake of nutrients and even heavy metals that cause water pollution, and the ability to metabolize these substances. This type of filtration is effective and resilient. There is no maintenance cost, unlike artificial filters that need repairs or replacement. Acquisition cost is zero since seaweeds can be sourced from the sea free of charge. However, there are limitations, depending on the type of IMTA system used. In land-based systems, the seaweed turnover is more rapid due to their death and decay in recirculating water. Generally, they perform better and for longer periods in flow-through systems or in IMTA modules operated in the sea, without containment structures.

Experiments on water quality and its effects on stocked tiger grouper (*Epinephelus fuscoguttatus*) and giant grouper (*E. lanceolatus*) when integrated with two organic extractives, namely, green mussel (*Perna viridis*) and sea cucumber (*Holothuria scabra*), and an inorganic extractive in the form of seaweed (*Kappaphycus striatum*) are under progress.

Conclusion

IMTA is a highly biodynamic system of low-carbon aquaculture. It represents an aquaculture model that mimics processes in nature through adaptive interventions informed by scientific evidence. The various attributes explained in this paper serve to demonstrate the synergy of multiple processes characterizing the biodynamics in IMTA and the dynamic equilibrium that so prevails for efficient organic production. A key component of environmental remediation is biofiltration. Efficiency of this process is variable, depending on biological, physical and chemical factors. Stacking rate of fed species, biofiltration substrate (media habitat) and other culture conditions elaborated in this paper aim at reducing and neutralizing the toxicity of nitrogenous waste, particularly ammonia and nitrite. Their toxicity to fed species can be contained by biological nitrification, whereby the excreted ammonia is successively oxidized to nitrite and nitrate. The nitrifying bacteria can act on ammonia and nitrite when the recirculating water flows over their attached media habitat. For this process to be efficient the environmental preferences of the nitrifying microorganisms need to be routinely monitored and satisfied. These include elevated dissolved oxygen level, neutral to slightly alkaline pH and moderately warm temperature. Microbiological studies are important not only for the sake of examining the concentration of nitrifying organisms but also other bacteria that thrive on residual organic matter. These latter types of microorganisms grow rapidly and can overwhelm the slower-growing nitrifying bacteria, cause overcrowding the of the niches available and impair the metabolic activities. Microbiological examination of samples from the IMTA system can help in identification of this category of bacteria and their role in the system. If they have any positive role, then measures can be taken to allow proliferation of both the types, provided it happens without any antagonism. It is worth examining the differences in the substrate preferences of these two types of microorganisms, so that suitable media habitats that are different and according to their selectivity, can be developed and placed in the IMTA system. A great deal of work remains to be done for IMTA to become a major interest in commercial aquaculture. The scope for innovative solutions in this area is enormous.

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