Integrated multi-trophic aquaculture: Integrated Marine Recirculated Aquaculture analysis

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1. Technical characterization of the system

Optimizing nutrient use has always been an objective in aquaculture, and particularly in recirculating aquaculture systems (RAS). Recirculation aquaculture is a technology for farming fish or other aquatic organisms by reusing the water in the production. It is based on the use of mechanical and biological filters in order to reduce the need for fresh and clean water while maintaining a healthy environment for fish (Bregnballe *et al.*, 2015). Integrated multi-trophic aquaculture (IMTA) is a system where the waste products from one food production process (fish or crustacean) are assimilated by other organisms (shellfish or seaweed) and converted into valuable products (Chopin *et al.*, 2001). Combining IMTA and RAS in marine aquaculture systems, abbreviated IMRAS (Figure 1), could be a solution to improve nutrient recycling, reduce water use and nutrient discharge while obtaining high yields (Neori *et al.*, 2000; Neori *et al.*, 2007).

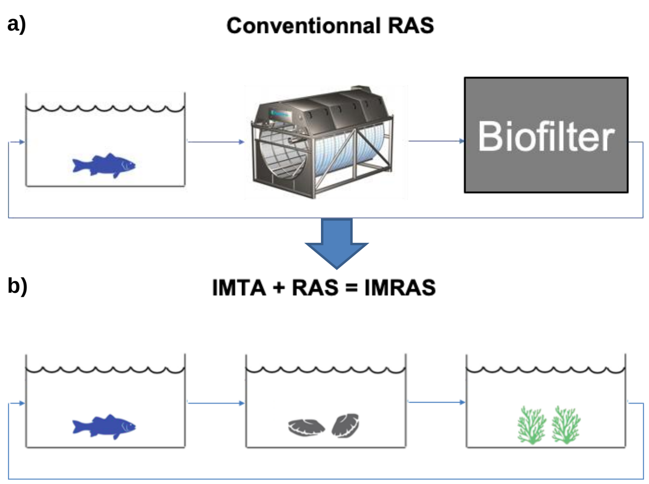

Figure 1. (a) Standard RAS with fish tank, mechanical filter and biofilter, (b) IMRAS with fish tank, shellfish tank which replace the mechanical filter and seaweed tank which replace the biofilter

2. Environmental analysis

2.1. Nitrogen release

Nitrogen is introduced in the system with fish feed enriched in proteins, and then converted and released as ammonia by fish and shellfish. Shpigel (2012) has demonstrated in a semi-recirculated system that more than 90% of the Nitrogen in the seawater brought by fish feed can be removed by extractive organisms such as shellfish and seaweed. Indeed, fish released nitrogen in the form of ammonia NH_3 which is often the preferred Nitrogen source for seaweeds (Lobban and Harrison, 1994; Carmona *et al.*, 2001). While shellfish remove the particulate nitrogen by filtering the water, seaweed absorb the dissolved nitrogen. For example, the IMTA-produced green algae *Ulva lactuca* delivers numerous assets for the aquaculture sector. It not only removes ammonia, but also supplies Dissolved Oxygen (DO). It also helps stabilize pH and keeps the water clear. This allows considerable water recycling and significant increases in overall water residence time (Neori *et al.*, 1996). This contributes to save water treatment costs and also convert fish waste into additional valuable crops (Bunting and Shpigel, 2009; Holdt and Edwards, 2014).

2.2. Phosphorus release

Phosphorus and its role are rarely investigated contrary to Nitrogen as Phosphorus effluent discharges are usually far less important than Nitrogen ones (Chopin *et al.*, 1999). Release of dissolved Phosphorus increases Phosphate PO_4^{3-} concentrations in the water, which is the form of Phosphorus most suitable for seaweed growth (Chopin and Wagey, 1999; Lobban and Harrison, 1994; Neori, 1996). However, phosphate does not constitute a threat to fish, yet it contributes to eutrophication (Neori et al., 2000). Many studies have demonstrated that seaweeds are able to extract phosphate from the water of the system (Neori *et al.*, 1996; Pagand *et al.*, 2000).

2.3. Organic matter release

The information concerning the management of organic matter (i.e. Carbon-based compounds) in IMRAS is very little studied in contrast to inorganic matter (i.e. Nitrogen and Phosphorus). Carbon is provided to the fish *via* the fish feed (Ebeling and Timmons, 2012) and to the algae via CO_2 fixation. Fish can use up to 22% of the Carbon contained in the fish feed for biomass increase and metabolism. The rest of the ingested carbon is either released under the form of CO_2 (52%) or excreted in a dissolved (0.7–3%) and solid (25%) form (Ebeling and Timmons, 2012). Suspended waste solids such as uneaten feed and fish feces, have to be removed as quickly as possible to prevent their accumulation within the RAS. Filter-feeding bivalves, such as oysters and mussels, are able to filter a large number of particulate organic matters, and cause sedimentation of the suspended solids (Pereira *et al.*, 2013; Zhou *et al.*, 2014). Moreover, daytime photosynthesis of *U. lactuca* (uptake of CO_2) can meet fish respiration (production of CO_2), thus balancing pH levels within safe limits regarding ammonia toxicity (Schuenhoff et al., 2003). Incidentally, deposited organic extractive species such as sea urchin and sea cucumber can be introduced in the system in order to complete the degradation of organic matter (Zhou *et al.*, 2014).

2.4. Water consumption

The water consumption of RAS is around 1m^3/kg of fish produced (Martin *et al.*, 2010). In an IMRAS, the production of wastes is reduced as well as the feed conversion ratio, leading to less water pollution and a smaller water consumption. Thus, the overall water residence time is increasing, and the need of renewal is less important.

2.5. Energy consumption

Standard RAS present a high energy consumption close to 300 MJ/kg of fish produced. This energy is mainly consumed on-site with 86% of the total (heating, pumps, etc.) (Aubin *et al.*, 2009). In comparison, IMRAS present on one hand the advantage of having no energy consumed by mechanical filters, but on the other hand, energy is consumed for powering lamps for algae for example. However, the lack of studies about the energy consumption of IMRAS compared to RAS doesn't permit to draw any conclusion over a higher or smaller consumption.

3. Productivity gains

For some IMRAS an overall yield can be observed two to three times higher than the one of a standard monoculture (Neori *et al.*, 2007). IMTA-produced Ulva have higher protein (between 26 and 37%) and lipid content (between 2 and 2.75%) compared to Ulva harvested from the wild (protein content ranging between 8.0 and 16.0%). They are also more productive and have less variability in biochemical composition, probably because of the uninterrupted and constant supply of nutrients from the fishpond effluents (Chopin *et al.*, 2001). Furthermore, producing Ulva in IMRAS can ensure significant sanitary safety compared to Ulva harvested in the wild (Shpigel et al., 2018).

Another example of improved productivity in IMRAS is the use of IMTA-produced-seaweed-based proteins for fish. Juvenile *Sparus aurata* show no difficulty in digesting fish feed based on poultry meal and *U. lactuca* protein (Shpigel *et al.*, 2017). In the study, fish performances were the same as fish fed with fish feed based on fish meal. The total cost of feed was reduced by \$0.25 kg^{-1} (Shpigel *et al.*, 2017).

4. Economic analysis

Stuart and Shpigel (2009) evaluated the economic potential of horizontally integrated land-based marine aquaculture. This study presents two different systems, in France and in Israel, and three scenarios for each country. First, the French system analysis shows that the no construction costs scenario, in the case of traditional aquaculture farm redevelopment, allows a payback period of 7.6 years and an intern return rate (IRR) of 3.6 %. In comparison, the baseline scenario, with construction costs, shows a payback period of 34.4 years and a negative IRR. Moreover, the study proves the need of a premium on the value of products: this scenario is based on the premise that consumers are willing to pay a premium of 20 % for products from horizontally-integrated systems. No construction costs plus premium on the value of products reveal a payback period of 4.1 years and an IRR of 19.4 %. A decrease in mortality and an increase in productivity reduce the payback period and raise the IRR. However, the decline in market prices significantly impacts the economic potential. For instance, in the Israeli case, the payback period goes from 4.5 years to 6.9 years and the IRR decreases from 18.0 % to 8.3 % when the price of the most profitable specie decreases, compared to baseline scenario.

To conclude, research shows that a horizontally integrated system is technically viable, but it is necessary to have production accorded to markets and seasonal needs (Neori *et al.*, 2001) and develop consumer acceptance (Sphigel, 2012). Moreover, it is necessary to control and optimize the production not to lose revenues (Neori *et al.*, 2001; Sphigel 2012).

5. Balance sheet

The objective is then to compare IMRAS to standard monospecific RAS. This relates to five criteria: nutrients, water, employment and economy. A score from -5 to +5 has been given to each of the criteria with the monospecific system as a reference (set to 0). The scores were established from the results found in the scientific literature as well as our personal point of view.

Figure 2 shows that IMRAS is better than standard RAS at optimizing nutrient usage since a large part is converted into valuable biomass by the different units of system. Although conventional RAS are already good at reducing the nitrogen discharge into the environment thank to nitrifying and denitrifying bacteria (Cahill *et al.*, 2010; Tal *et al.*, 2009), according to Metaxa *et al*. (2006), green algae are better than biofilters for reducing the NO_3 and the PO_4^{3-} concentrations. Indeed, contrary to bacteria-based biofilter which only converted toxic NH_3 into much less toxic NO_2, seaweeds are able to extract NH_3 from the water and prevent the accumulation of NO_2. Moreover, seaweeds and shellfish produced economically valuable biomass unlike mechanical and bacteria-based filters. However, seaweeds have shown a seasonality with good absorption in spring and summer, and a less efficient absorption in winter. It requires also a greater amount of surface area and land than bacteria-based biofilters (Metaxa *et al*., 2006). As a consequence of the previous result, IMRAS are also better at recycling water as water renewal is less important than monospecific system.

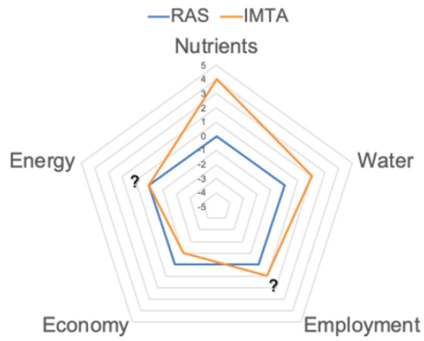

*Figure 2. Radar diagram on environmental, social and economic aspects of IMRAS and conventional RAS as a reference (**?**: no data available)*

Concerning the employment, there is no study yet which presents this aspect. Nonetheless, IMRAS are expected to create more jobs as specialists for each species produced are required. This system is also economically viable in theory, but it is more complex than monospecific system because its viability depends on a lot of parameters (consumer acceptance, development of new markets, etc.). Lastly, there is no study which quantified energy consumption. Still, IMRAS and monospecific system are expected to be equal on this point. In fact, a large part of energy use in RAS is due to water temperature regulation and water recirculation.

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