Integrated multi-trophic aquaculture: aquaponics analysis

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1. Technical characterization of the system

According to Goddek *et al.* (2019), aquaponics is defined as an integrated multi-trophic, aquatic food production approach comprising at least a recirculating aquaculture system (RAS) and a connected hydroponic unit, whereby the water for culture is shared in some configuration between the two units (figure 1). Not less than 50% of the nutrients provided to the plants should be fish waste derived. Here we discuss about coupled aquaponics systems which is the simplest system to understand and manage and thereby the most widespread.

The coupled aquaponics principle combines three classes of organisms: aquatic organisms, bacteria and plants that benefit from each other in a closed recirculated water body. The water serves as a medium of nutrient transport, mainly from dissolved fish waste, which is converted into nutrients for plant growth by bacteria. These bacteria oxidize ammonium to nitrite and finally to nitrate (Goddek *et al.*, 2019).

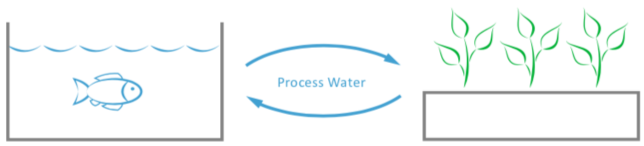

Figure 1. Aquaponics: coupled (one-loop) system

2. Environmental analysis

2.1. Nitrogen release

Yogev et al (2016) estimates that 90% of the nitrogen introduced into an aquaponics system is fixed by fish and plants and only 10% is lost in gaseous form. Part of the food distributed to fish that is not completely consumed and decomposes on the bottom of the basins. Fish assimilate 21.0-27.9% of the nitrogen provided as food (Wongkiew *et al.*, 2018). Yogev et al (2016) reports similar results with 29% of the total nitrogen supplied to fish being assimilated. Unconsumed food, faeces and ammonia excretions account for 7.2-49.4% of the total nitrogen supply and are dependent on the species being raised (Wongkiew *et al.*, 2018). The fate of nitrogen follows two microbiological processes. Solubilization consists of the degradation of complex organic molecules from faeces and uneaten food in the form of ions that can be assimilated by plants. It is mainly carried out by heterotrophic bacteria (*Rhizobium sp., Flavobacterium sp., Sphingobacterium sp., Comamonas sp., Acinetobacter sp., Aeromonas sp. and Pseudomonas sp.*). Nitrification is a two-step process in which ammonia or ammonium excreted by fish is first transformed into nitrite and then into nitrate by specific chemosynthetic aerobic autotrophic bacteria (Goddek *et al.*, 2019). Nitrification takes place mainly in the biofilter. The amount of nitrogen captured by plants depends on the crop species. It is 44% of the total nitrogen introduced with tomatoes while it is 1.7% of the total nitrogen introduced with chives (Wongkiew *et al.*, 2018).

The observed nitrogen releases come from two major pathways: denitrification and nitrification denitrification. Denitrification is the mechanism for transforming nitrate into nitrous oxide and finally nitrogen gas under anoxic conditions (Wongkiew *et al.*, 2017). Nitrification denitrification is the mechanism during which oxidation of ammonia and denitrification take place simultaneously in the absence of the nitrite oxidoreductase enzyme and with a low oxygen concentration. Under these conditions, ammonia is oxidized as nitric oxide and nitrous oxide (Wongkiew *et al.*, 2017). The nitrous oxide produced by these two reactions is a powerful greenhouse gas (Randeniya *et al.*, 2002). Nitrous oxide emissions from aquaponics are considered insignificant compared to nitrogen emissions, respectively 1.5-1.9% and 32% of the total nitrogen supplied (Hu *et al.*, 2015).

2.2. Phosphorus release

Knowledge of the fate of phosphorus in aquaponics is limited. Phosphorus is available to plants in its orthophosphate forms ($H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) (Goddek *et al.*, 2019). According to the results of Cerozi et al (2017), the uptake of phosphorus by fish and plants, respectively 42.3%

and 29.4%, represents 71.7% of total phosphorus intake as food. Schneider et al (2004) reports that 30 to 65% of the phosphorus in food is inaccessible to plants because it is trapped in sediment. Yogev *et al.* (2016) estimates that this loss can reach 85%. Phosphorus can precipitate as struvite and/or hydroxyapatite (Goddek *et al.* 2019). This phosphorus-enriched sludge can cause eutrophication when it's discharged into the external environment. Ways are being explored to treat sludge in order to reduce its phosphorus load, in particular with UASB (upflow anaerobic sludge blanket) / EGSB (expanded granular sludge bed) sequential bioreactors. Approximately 25% of the phosphorus, potassium and calcium contained in the sludge can be recovered with this method (Goddek *et al.*, 2018).

2.3. Organic matter release

Carbon is provided to the fish via the feed (Timmons *et al.*, 2013) and to the plants via CO_2 fixation. Fish can use 22% of the carbon contained in the fish feed for biomass increase and metabolism. The rest of the ingested carbon is either expired under the form of CO_2 (52%) or excreted in a dissolved (0.7–3%) and solid (25%) form (Timmons *et al.*, 2013). Those results are confirmed by Yogev *et al.* (2017) who found 27% of the applied carbon, accumulated as fish biomass, 39% was collected as sludge in the solids filter and 34% was aerobically degraded. Plants can use the expired CO_2 as their own carbon source (Körner *et al.*, 2017). The digestibility of the feed and the biodegradability of the sludge car be influenced by the type of carbohydrates used in fish feed (starch or non-starch polysaccharides) (Meriac *et al.*, 2014). It is possible to increase the amount of organic matter breakdown up to 34% of the organic carbon in the feed by using denitrification coupled with UASB reactor (Yogev *et al.*, 2017).

2.4. Water consumption

Water savings are substantial. It needs 10% less of water compared to a classic pisciculture and 90% less compared to conventional agriculture. Different savings could be considered. First, common water is used by both plants and fish. Little new water is added daily compared to a classic aquaculture (1-2% water of total volume added *vs* 20-25% in extensive system). It needs less water per kg of fish. For instance, to produce one kg of fish you need 0.32 m^3 in aquaponics system instead of $5m^3$ in extensive system (Hafedh *et al.*, 2008). Water losses are only due to evapotranspiration and there are no losses by infiltration. This water could be condensate and recycled. Studies are needed to assess the energy cost. Little water added could be rainwater instead of tap water (Kloas *et al.*, 2015). Wastewater flow rate is 100 to 1000 times lower and less concentrated than in conventional system (Blidariu and Adrian Grozea, 2011). A more economic and easier water treatment is possible.

2.5. Energy consumption

Energy is used for greenhouse warming and aquaponic system. Consumption depends on system configuration and geographic location. Considering the location, the origin of energy could change. For instance, in desert, solar energy will be preferred while geothermal energy will be recommended in cold areas (Goddek et al., 2015). Besides, the more you increase pond temperature, the more energy you save . Indeed, the aquaponic system has a high calorific capacity that serves as both a heat source and a buffer. So energy savings are made in the greenhouse. (Meriac *et al.*, 2014). A study shows that it's possible to make great savings considering the water aeration system. It said that if semi aeration or intermittent aeration is used, cost energy could decrease by 44% (Yingke *et al.*, 2017). Finally total reduction of power consumption could reach around 50% (Van Ginkel *et al.*, 2017).

3. Economic analysis

Aquaponics have emerged with environmental considerations where the use of water and fertilizer is reduced thanks to the valorization of livestock manure (Greenfeld *et al.*, 2018; Foucard *et al.*, 2019). The growing interest arouses questioning about the economic viability of large systems, as well as their ability to compete economically with the latest generation of hydroponic and aquaculture systems (Goddek *et al.*, 2019). No publication refers to a gain or loss of productivity of the aquaculture unit in aquaponics. Aquaponics "is just starting to be totally mastered from a technical point of view, it is now a question of comparing these production systems with analyzes from the economic point of view" (Foucard *et al.*, 2019). Although the technology has been known for several decades, the economic viability of commercial systems is still in question. The models developed are often too enthusiastic and / or based on unrealistic expectations (Turnšek *et al.*, 2019). Thus, aquaponics has even been described as a "virtual industry" (Greenfeld *et al.*, 2018). However, some publications conclude that aquaponics may be profitable (Heidemann, 2015; Quagrainie *et al.*, 2018; Trintignac *et al.* 2018; Asciuto *et al.*, 2019).

Other studies indicate an economic viability to be qualified: the costly aquaculture production does not make it possible to expect a sufficient return on investment with regard to the risks engendered (Bosma *et al.*, 2017) and the combination of the two compartments, although environmentally beneficial, does not guarantee sufficient productivity to compete with hydroponics alone (Vergote and Vermeulen, 2012).

These trends are confirmed by two surveys where only 11.8% at the European level (Villarroel *et al.*, 2016) of the operators indicate that they are profitable. Nevertheless, it appears that aquaponics is proving to be a complex and expensive technology but the integrated combination of two production plants could allow a reduction in fixed (infrastructure and management) and variable (input-related) costs, sharing or decreasing them (Vergote and Vermeulen, 2012; Asciuto *et al.*, 2019).

4. Balance sheet

To conclude, a comparison has been made between an aquaponics system and an extensive monospecific system. This relates to five criteria: Environment (energy, nutrients, water), social and economic. A score from -5 to +5 has been given to each of the criteria with the extensive 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. The figure 1 introduces those results.

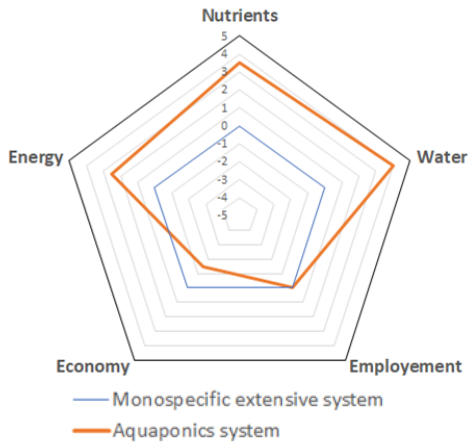

Figure 2. Radar diagram on environmental, social and economic aspects of aquaponics and extensive monospecific systems

The results found show that aquaponics systems are better on the environmental criteria because of a better water use, the recycling of nutrients and thus a lower consumption of energy. The social aspect has been ranked equally to the reference because of a deficiency of informations about that subject. The economic aspect has ranked lower than the reference because of a profitability still in question in the field.

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