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From freshwater to marine aquaponic: new opportunities for marine fish species production

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Abstract
Due to the increasing world population, by 2050 food production should be increased of about 70% to 100%. Tanks to the lowest "carbon footprint", aquaculture seems to be the most sustainable system for producing food (protein) of animal origin. Despite that, progress can be done for further improving aquaculture sustainability through the "aquaponic" system (IAS).
A IAS is based on the bacteria nitrogen cycle which convert fish waste (faeces and uneaten feed) into nitrite and nitrate, this latter absorbed by plants grown in the hydroponic section of the aquaponic system; as a results, water is "depurated" and recycled into the fish tanks.
Advantages of this system are the high productivity, the reduced water requirement, the neglectable waste production, the reduced plant disease incidence and pesticides utilization, the modularity of the system which allow its uses for a wide range of purposes (urban agriculture, people resilience in developing countries, marginal land exploitation, etc.); for a contrary, disadvantages are the relevant initial investments, the required high education level of the employees, the "sensitivity" of the systems and some minor others.
A relevant future challenge for scientists is to develop "marine aquaponic system" for producing more valuable fish and crops, interesting also for the EU and 'developed countries' market.

Key words: Aquaculture, aquaponic, fish production, food security, sustainability

Introduction

It is expected that the world population will be growing up to 9 billion people by 2050 (Bernstein, 2011, 1). This fact implies that the global demand for food have to be further expanded of about 70-100% (Godfray *et al*., 2010, 2; World Bank, 2008, 3). In this context, the agriculture sector, which already plays a central role in ensuring food security (Rivera-Ferre *et al.*, 2013, 4), have also to respond to one of the greatest dilemmas of 21st century: how to produce more food using less resources and minimizing the environmental impact? (Velten *et al.*, 2015, 5). Among the agricultural production systems, aquaculture seems to be the most suitable to solve this dilemma.

From Aquaculture to Aquaponics

Starting from 1990, the growth rate of aquaculture sector has been estimated to be 7.8% per year, surely the most interesting among all the food production sectors (Troell *et al*., 2014, 6), it represents the major source of income for about 11 million of people (FAO, 2011, 7) and main source of animal protein for 1 billion of people (Tidwell and Allan, 2012, 8); moreover, thanks to the excellent feed conversion rate (FCR), it shows the lowest carbon footprint. Besides that, aquaculture causes a strong exploitation of fish's wild stocks (Adler *et al.*, 2008, 9) due to the necessary huge inclusion of fishmeal and fish oil in fish feed (Alessio *et al*., 2001, 10); moreover, aquaculture contributes to eutrophication and pollution of aquatic ecosystems (Primavera, 2006, 11); finally aquaculture require large quantities of water, which may vary from 3000-45000 litres/ kg of fish produced (Verdegem *et al*., 2006, 12).

Modern aquaculture mainly relay on RAS systems. RAS is "closed" loop system that reuse the water within the rearing system. In these systems, the water reutilization rate may range between 80 and 99% and that reduce the environmental impact of aquaculture and water requirement (Ebeling and Timmons, 2012, 13; Kingler and Naylor, 2012, 14).

Hydroponics is a method of cultivation of plants that do not require the use of soil (Malorgio *et al*., 2005, 15); in these systems, water and nutrients are supplied trough a nutrient solution in which fertilizers are dissolved in appropriate concentrations (Putra and Yuliando, 2015, 16). There are several models of hydroponic systems and while some of them (*Nutrient Film Technique* and *Deep Water Culture*) do not require the use of any substrate, some others (*Media Bed Technique*) may require the use of an artificial and inert substrate for providing mechanical support to plant's roots (FAO, 2014, 17; Lakkireddy *et al*., 2012, 18). Avoiding contact between plants and soil, hydroponic system allows a better control of plant conditions (Tesi, 2008, 19); also, hydroponic repersent a solution in those areas where the lack of fertile land and water cause a strong competition for resources (FAO, 2014, 17). Despite that, some factors are the main limitations to the development of this technique as the high initial investments, the need for specialized technical personnel (Malorgio *et al*., 2005, 15) and the high cost of fertilizers (Hochmuth and Hanlon, 2010, 20).

Finally, IAS is a "systems that grow additional crops by utilizing by-products from the production of the primary species" (Rakocy, 2012, 21); in practice, when terrestrial plants (secondary crops) are grown in conjunction with fish (primary cultures), the system is called aquaponic system and consists of a combination of a RAS and a hydroponics system (FAO, 2014, 17). Aquaponic systems are based on natural biological processes (Tyson *et al*., 2011, 22) such as nitrification and phytoremediation; moreover, they allow to obtain intensive production, comparable with RAS and hydroponics separately, contributing to improve sustainability and to reach food security goals; in this way significant economic and social benefits are also achieved (FAO, 2014, 17).

Theoretical and technical basis of aquaponic systems: from fish to vegetables

In aquaculture, about 5% of feed is not consumed by farmed fish, while the remaining 95% is ingested and digested (Khakyzadeh *et al*., 2014, 23); of this share, 30-40% is retained and converted into new biomass, while the 60-70% is released in form of faeces, urine and ammonia (FAO, 2014, 17). Studies

refer that 1 kg of feed (30% crude protein) globally release about 27.6 g of N as well as 1 kg of fish releases about 577 g of BOD, 90.4 g of N and 10.5 g of P (Tyson *et al*., 2011, 22).
In aquaponic the waste products of the fish metabolism and uneaten feed are used as fertilizers for crop production, transforming a waste into a valuable resource. In this transformation, the role of bacteria is crucial. The output water from the fish tank is conveyed to a mechanical filter for the separation and removal of the most large solid particles; afterwards, the water reaches a biofilter, primary site of bacteria nitrification; this process consist in the oxidation of ammonia (NH_3) and the ammonium ion (NH_4^+) to nitrates (NO_3^-), more accessible form of nitrogen for plants (FAO, 2014, 17; Rakocy, 2012, 21). The conversion takes place through two successive reactions and involves two distinct groups of nitrifying bacteria: *Nitrosomonas*, by which the ammonium ion is converted into nitrite (NO_2^-); *Nitrobacter*, which finally transform the nitrite to nitrate (Alessio *et al*., 2001, 10). Nitrification and a vital bacterial colony are therefore essential conditions for an aquaponic system to work properly. Another important group of aerobic bacteria is heterotrophic bacteria that are involved in the mineralization of solid waste (FAO, 2014, 17). Hence, the nitrates and other nutrients enriched water leaves the biological filter and circulates towards the hydroponic section where the phytoremediation process takes place (FAO, 2014, 17) and nitrates in the water may be reduced by more than 97% (Lennard, 2006, 24); a final UV sterilization allows the water to return in the fish tanks. Studies have shown that on average, for every 60-100 grams of feed supplied, a square meter hydroponics culture is required for a just poor water purification (Rakocy *et al*., 2006, 25); also, a square meter of hydroponic culture can remove 0.83 g of N and 0.17 g total P (Tyson *et al*., 2011, 22).
In relation to the technical basis of aquaponic systems,there is a wide variety of aquaponic systems even though they all share some essential components: a fish tank, a mechanical filter, a biofilter, a hydroponic container for plant growth and a sump (FAO, 2014, 17). In the fish tanks, the stocking density may vary from 20 kg/m^3 (FAO, 2014, 17) up to 70-80 kg/m^3; just in some specific cases it seems to be possible to reach stocking density of about 140-200 kg/m^3 but the water retention time could not be longer than 1.2 hours in order to avoid the accumulation of ammonia after feed administration (Pantanella, 2012a, 26). Among mechanical filters, the most used is "clarifier" (FAO, 2014, 17) that removes about 59% of total solid waste, with a water retention time of 20 minutes (Pantanella, 2012a, 26) and a volume of 10-30% to the rearing tank (FAO, 2014, 17). According to FAO (2014, 17), the minimum volume of the container should be 1/6 of the fish tanks and the most frequently used substrates are Bioballs® (500-700 m^2/m^3) and volcanic gravel (300 m^2/m^3). The various types of aquaponic systems are named after the hydroponic technique used for the cultivation of plants. MBT is the most common method adopted in small-scale aquaponic production (Rakocy, 2012, 21), and the porous substrate provides support to the plants and it works as mechanical and also "bio" filter (FAO, 2014, 17). Conversely, the NFT method and DWC are suitable for commercial aquaponic systems but, unlike the method with the growth beds, they require a mechanical filter and a biofilter. The water output from hydroponic containers by gravity falls into the sump, a water collection tank (Rakocy, 2012, 21), where is located the submersible pump.
The Feed Rate Ratio (FRR) is the ratio between the amount of feed administered on a daily base, and the area used for hydroponic cultures. The calculation of the FRR strictly affects the rate and extent of accumulation and removal of nutrients from the fish tanks as well as the integration of macro- and micro-nutrients required in aquaponics to maximize the yield of the crop production (Lam *et al*., 2015, 27). According to Rakocy (2012, 21), the optimal ratio is 57 g of feed per day per meter of hydroponics surface area; it is also recommended to maintain a ratio between rearing tank and hydroponic containers of 1:7.3. As regards the water quality, according to FAO (2014, 17) a good compromise is achieved when the system ensures temperatures between 18-30 °C, a pH of 6-7, ammonia and nitrates less than 1 mg/L and DO exceeding 5, and through the administration of 60-100 g of feed per m^2 of hydroponic surface area (Rakocy *et al*., 2006, 25).

Fish and plant species

Fish species that have been proven to be suitable for suitable for aquaponic production are Nile tilapia, trout, barramundi, murray cod, African catfish and Koi carp (Kloas *et al*., 2015, 28; Palm *et al*., 2014, 29; Roosta, 2014, 30; Endut *et al*., 2011, 31; Nelson, 2007, 32; Lennard and Leonard, 2006, 33; Rakocy *et al*., 2006, 25; Savidov, 2005, 34; Adler *et al*., 2000, 35. Among the cultivated plant species, the most widespread are lettuce, tomato, basil, eggplant, pepper and water spinach (Khater *et al*., 2015, 36; Palm *et al*., 2014, 29; Endut *et al*., 2011, 31; Nelson, 2007, 32; Rakocy *et al*., 2006, 25; Savidov, 2005, 34; Adler *et al*., 2000, 35).

Marine aquaponics

Freshwater aquaponic is the most widely diffused and described aquaponic technique. The limited resources of freshwater for agriculture and aquaculture, as well as the progressive increase of the soil salinity worldwide (Turcios and Papenbrock, 2014, 37), are leading on one side to the more frequent use of alternative water resources such as brackish water (Pantanella, 2012a, 26), on the other side to the use of salt tolerant or resistant plants (Joesting *et al*., 2016, 38; Turcios and Papenbrock, 2014, 37; Buhmann and Papenbrock, 2013, 39). According to Orellana *et al*. (2013, 40), nowadays the most innovative strategy in aquaculture seems to be the development of “traditional” IAS based on marine water; to this purpose, halophytes plants might be fruitfully grown. To this regard, several studies suggest that the waste produced by marine aquaculture facilities can be successfully used to irrigate the salt tolerant or resistant plant species (McIntosh and Fitzsimmons, 2003, 41; Dufault *et al*., 2001, 42; Dufault and Korkmaz, 2000, 43). From these considerations comes the interest in “marine aquaponics”, where euryhaline fish species and halophytes plants are cultured. Euryhaline species, which can live in a wide range of salinity (Alessio *et al*., 2001, 10), demonstrate a remarkable compatibility with a wide variety of plant species such as algae, halophytes plants and other vegetable crops (Pantanella and Colla, 2013, 44). Among the euryhaline species with great potential for marine aquaponic there are also European sea bass (*Dicentrarchus labrax*) and Gilthead sea bream (*Sparus aurata*). In marine aquaponics the process of phytoremediation must be done by the plant species that can tolerate higher salt concentrations to at least 5 g/L as halophytes plants (Ayers and Wescott, 1989, 45). The ideal salinity conditions for their growth vary from 1/3 to 1/2 salinity of the sea (between 10 and 20 g/L) but some species as *Distichlis palmeri* are also tolerant to conditions of hipersalinity (Pantanella and Bhujel, 2015, 46). The halophytes plants have been studied for their interesting properties and they resulted of interest for many fields such as for food production, oil industry, pharmaceutical and nutraceutical sector (Buhmann and Papenbrock, 2013, 39; Koyro *et al*., 2011, 47). The main halophilous species grown for veggies production are samphire (*Chrithmum maritimum*), the agretti (*Salsola soda*) and several species of the genus *Salicornia,* while other halophytes are grown for grain production such as the quinoa (FAO, 2014, 17). In addition to halophytes, marine aquaponics can grow horticultural crops using brackish (5-30 g/L salinity) water (Pantanella, 2012b, 48). Many of them belong to the family *Chenopodiaceae*, such as chard (*Beta vulgaris* var. *Maritima*) and beet (*Beta vulgaris* var. *Cycles*), and easily grow in salinity of 3,5-7 g/L. Other species such as the common tomato (*Lycopersycon esculentum*), the cherry tomatoes (*Lycopersycon esculentum* var. *Cerasiformee*) and basil (*Ocimum basilicum*) can achieve remarkable productions up to 1/10 (4 g/L) of the sea salinity (Pantanella and Bhujel, 2015, 46). Finally the integration between marine aquaponics with the cultivation of algae is a good alternative if you cannot use low-salinity water (Pantanella and Bhujel, 2015, 46). Among the algal species of remarkable interest are considered spirulina (*Arthospira platensis*), chlorella (*Chlorella* spp.) and seaweed nori (*Porphyra yezoensis* and *Porphyra tenera*).

There is considerable interest in marine aquaponics and its main advantages are: reduced dependence on freshwater (limited resource); practiced in a controlled environment (in land and/or indoor); opportunity to reuse of waste, virtually eliminating sea pollution; intensive productions, quantitatively comparable with conventional systems; high food safety standards (Boxman *et al*., 2015, 49; Pantanella and Colla, 2013, 44). Moreover, due to its versatile configuration and low water requirement, marine aquaponic can be lead on fertile coastal areas as well as in arid deserts, or in urban and peri-urban settlements (Pantanella, 2012b, 48). An additional advantages of marine aquaponic is that the fish and vegetable production is represented by species of high commercial value such as Gilthead sea bream and European sea bass; according to ISMEA, an Italian statistic Institute (ISMEA http://www.ismea.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/4471, 5.11.2015), the market price of these species are 9 €/kg and 6 €/kg, respectively. On the crop side, the sea "agretto" (*Salsola soda*), is commonly sold at a maket price of 4.0-4.5 €/kg (Pantanella, 2012b). In contrast, marine aquaponic still suffer for its poorly organized system, probably due to lack of demand for species of halophytes market and/or to the difficulties in countering the negative effects of salinity (Boxman *et al*., 2015, 49). Also a few production attempts have been successfully carried out by Main *et al*. (2015, 50), rearing Red drum (*Sciaenops ocellatus*) and Florida pompano (*Trachinotus carolinus*) as fish species and Smooth Cordgrass (*Spartina alterniflora),* Black Needle Rush (*Juncus romerianus*), Red Mangrove (*Rhizhophora mangle*) as vegetal species, and by Boxman *et al*. (2015, 49) using two halophytes species (*Batis maritima* and *Sesuvium portulacastrum*) and again *Sciaenops ocellatus* as fish specie. At the end of this latter experiment, products not only have been proven to be suitable for marine aquaponic production but also achieved good results in the local market (Boxman *et al*., 2015, 49).

Production statistics

A recent survey carried out by Love *et al*. (2014, 51) showed that in 2014-2015, 32% of about 1000 people employed in the aquaponic sector, were engaged in the commercial sale of aquaponic products. The average amount of fish harvested by commercial producers was between 23-45 kg/year, while it was 45-226 kg/year for the plants (Love *et al*., 2015, 52); this production represented a primary source of income for 30% of the interviewed people. Furthermore 31% of them declared that their activity was profitable (Love *et al*., 2015, 52).

Conclusion

Despite globally only few attempts have already been carried out so far, aquaponic seems to be a suitable tools to overcome the contradiction between the necessary intensification of food production and its sustainability; obviously, new studies and researches are needed in order to better define aquaponic profitability according to its type of set up.
Moreover, it is worthy to highlight the important social role that aquaponic system may play in the economy of small communities in the urban and peri-urbans settlements, of the developing countries to improve people resilience (e.g. in the refugees camps) and as an educational tool for teaching chemistry, physiology, anatomy and botany to students and workers.
Finally, marine aquaponic production may help to improve profitability diversifying the whole production and culturing high value products; brackish water sources exploitation and other marginal lands worldwide use for agricultural purposes, are additional advantages related to the marine aquaponic.

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