Aquaponics Guidelines

Editor: Ragnheidur I. Thorarinsdottir

Co-funded by the Eco-innovation
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Summary

Aquaponics is a combination of the words aquaculture (cultivating fish) and hydroponics (growing plants in water without soil) and the eco-innovative technology behind the concept is a combination of the two production systems into one. It is driven by a microbial ecosystem that assists in converting fish effluents into usable plant nutrients while helping deliver plant nutrients across root cell walls. In an aquaponic system, water is kept in circulation. Waste water from the fish is used as nutrients in the horticultural part of the system where plants take up the nutrients provided by the fish waste and cleanse the water before being returned to the fish. Aquaponics is a resource efficient closed loop food production system, mimicking nature itself. This relates to cradle-to-cradle design presenting eco-effectiveness moving beyond zero emissions and produce services and products taking into account social, economic and environmental benefits (McDonough and Braungart, 2002; Braungart et al., 2007; Kumar and Putnam, 2008).

Small private and/or educational/research aquaponic systems have been built in several places around the world and the technology is becoming increasingly popular. There is rising interest for industrial show cases, to test whether it can be a profitable business to run large-scale aquaponic systems, raising fish and plants simultaneously for the market. Commercial-scale facilities, although limited in number, can now be found across the globe that incorporate modern technology based on automatic control, improved system balance and health and safety.

The conditions to implement an aquaponics industry in Europe are currently being evaluated and several pilot units of different sizes and design have been constructed in most European countries. Only very few of them reach a production area of more than a few square meters (m^2). However, systems are now planned or have been built on a medium scale of a few hundreds and up to a few thousand m^2.

These guidelines present a short history of aquaponics as well as the current status of aquaponics development in Europe. The main types of aquaponics system design are outlined along with guidelines for how the environmental parameters need to be controlled. Moreover, in this guiding document the production parameters are described, including suitable choices of plants and fish species. The market conditions, certification and regulatory issues are discussed, also including added value opportunities linked to experience and educational tourism, technology development and byproducts, e.g. from sludge processing. Finally, conclusions and future perspectives are put forward.

It is the hope of the authors that the guidelines can be of value to aquaponics hobbyists as well as others who plan to develop commercial scale aquaponics. The guidelines are built on collaborative work between two European projects: the Leonardo project **EuroPonics** (www.aquaponics.is/europonics) that focuses on

vocational training in aquaponics and the EASME project **EcoPonics** (www.aquaponics.is/ecoponics/) which aims to establish commercial aquaponics in Europe. Further contributors are aquaponics specialists from the management committee of the COST Action FA1305 **The EU Aquaponics Hub** – Realising Sustainable Integrated Fish and Vegetable Production for the EU (www.euaquaponicshub.com/).

Keywords: Aquaponics, aquaculture, hydroponics, zero-waste, renewable energy, tourism

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1 Introduction – What is aquaponics?

Aquaponics is a food production method for producing terrestrial plants and aquatic organisms that combines two traditional production systems – recirculating aquaculture and hydroponics. Aquaponic systems recirculate and recycle all the water and nutrients through symbiotic processes preventing discharge of eutrophic or organic wastes. In November 2010, *The Aquaponics Gardening Community*[1] put forward the following definition:

> *Aquaponics is the cultivation of fish and plants together in a constructed, recirculating ecosystem utilizing natural bacterial cycles to convert fish waste to plant nutrition. This is an environmentally friendly, natural food-growing method that harnesses the best attributes of aquaculture and hydroponics without the need to discard any water or filtrate or add chemical fertilizers.*

Aquaponics is an ecosystem of plants, fish, bacteria, sometimes worms and/or other organisms, growing together symbiotically (Figure 1.1). The beneficial bacteria convert the waste water from the fish into plant food, and the plants filter the waste water for nutrients before the water returns back to the fish.

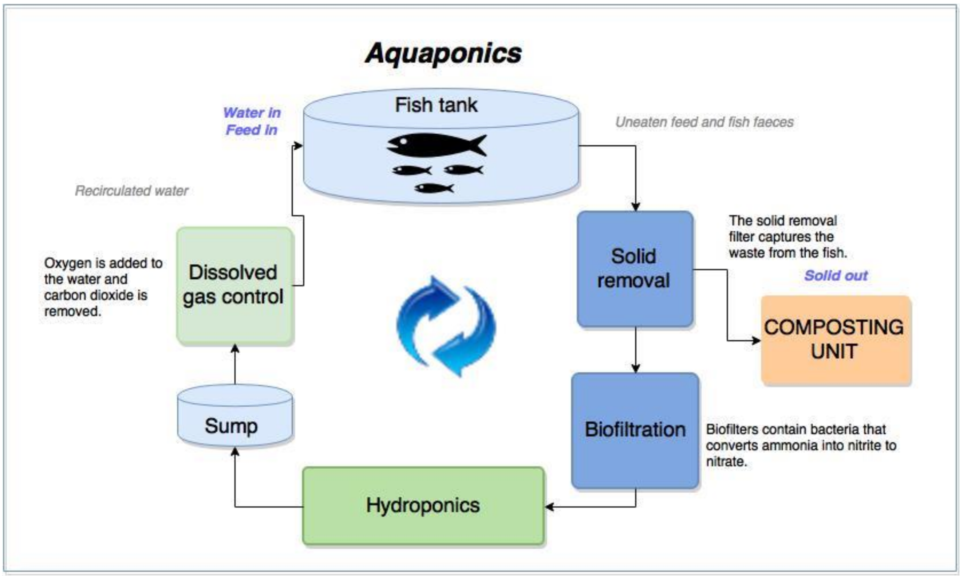

Figure 1.1 Aquaponic system

Many of today's aquaponic systems circulate water and nutrients from fish to plants to fish as shown in Figure 1.1 and the water quality is specifically managed to fit the requirements of the fish species being cultured and suitable plants are chosen to fit

[1] http://community.theaquaponicsource.com/

the fish environment. It is not always guaranteed that the fish preferences are completely aligned with the optimum requirements of the plants. This calls for compromising of the plant's needs, and as a result they may not achieve their full growth capacity. Therefore another design has been investigated in which the water flow is divided into two independent systems that can occasionally communicate whenever plants need a boost in nutrients or fish require reclaimed water from plants to dilute the wastes accumulating in the fish sub-unit. This solution, which is referred to as a "decoupled" system (Figure 1.2) would better secure optimal environmental conditions for both the plant and fish production units and may become a cornerstone towards the implementation of large commercial aquaponic systems. The risk mitigation factor alone has increased the use of decoupled systems globally. If a problem occurs in the fish or the plant components, each section can be isolated and run as a stand-alone aquaculture or hydroponic system, while the problem is addressed.

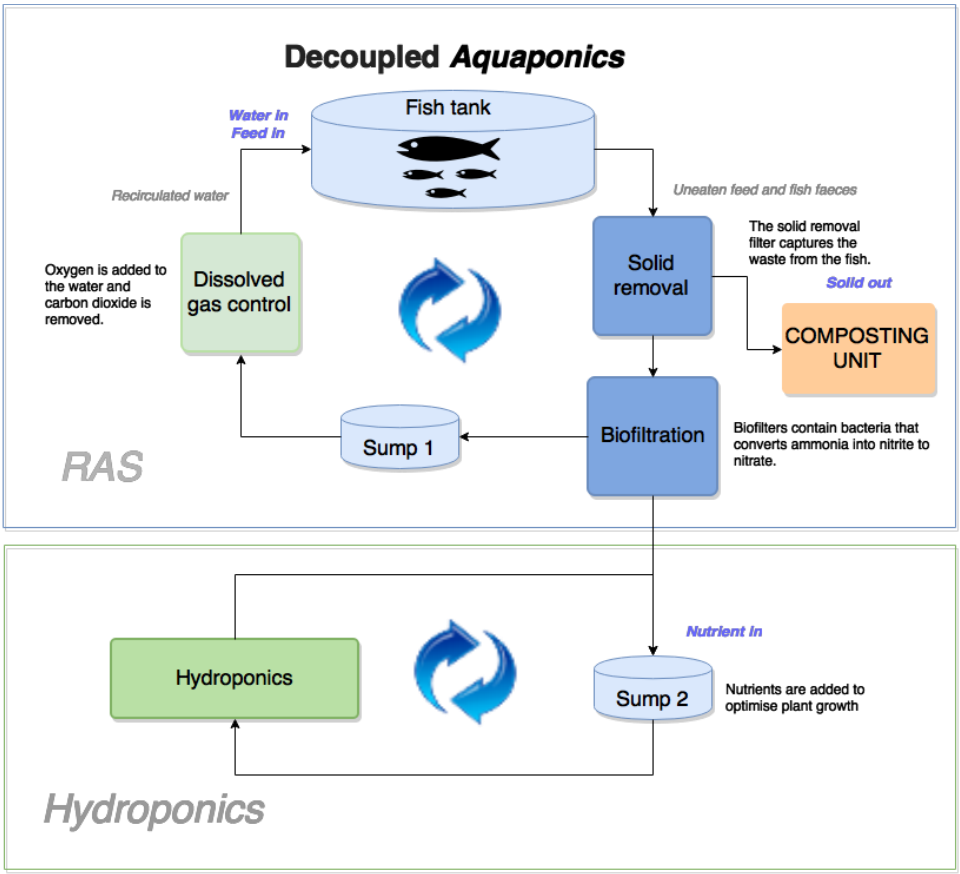

Figure 1.2 Decoupled aquaponic system

Many options exist for solid waste management in aquaponic systems. Discharged solid wastes may be utilized to create value added products such as compost or on-farm seeding media (Danaher et al., 2011; Pantanella et al., 2011a). Solids can also be mineralized in a separate loop, allowing dissolved nutrients to be returned to the system. Rakocy et al. (2005) described mineralization rates of discharged effluents from an aquaponic system operated in the US Virgin Islands. Several ideas are being tested aiming for zero-waste solutions, using the sludge as e.g. feed for crayfish, farming of worms and/or black soldier flies, or making fertilizer or biogas through aerobic or anaerobic digestion.

2 History of aquaponics

Aquaponic systems have been developing and the interest in the field has been increasing, not least due to the pressure to produce more food in a sustainable manner for a rapidly increasing world population (Goddek et al., 2015; Mageau et al., 2015). Increasing energy costs and dwindling natural resources such as phosphorous and water (Sverdrup and Ragnarsdottir, 2014) are forcing the world to take action and change present-day food production systems. Scientists and innovation companies have started national and international collaboration projects for development and future possibilities of local and sustainable food production. Innovations include aquaponics, production of insects and other products - what previously would have been thought of as far flung ideas.

One of the main challenges regarding aquaponics and other integrated production techniques is to join two or more different production systems together. Aquaculture and horticulture are quite different production technologies and joining them into a simple aquaponics circulation may result in a stable production system with optimum output. However, it has hitherto proved to be difficult to join skills, knowledge and traditions from different production cultures.

Aquaponics in the modern era began in areas that are limited in fresh water, particularly Australia and other arid regions such as the US Virgin Islands. With limited fresh water resources and an increasing demand for food to supply a growing population, these regions began to link fish and plant culture together in an integrated system. While the Australian movement initially focused on small-scale food production, the University of the Virgin Island began to trial commercial levels of production in an attempt to create a viable industry.

2.1 University of Virgin Islands (UVI)

The pioneers in aquaponics include scientists at the University of Virgin Islands (UVI), led by Dr. Jim Rakocy who began aquaponics research in the late 1970´s. This system has been the inspiring layout of several commercial systems in the US and systems built by several growers and researchers worldwide. The University of Virgin Islands has been active in aquaponics research for more than thirty years and has a globally recognized aquaponics education program. The system developed at UVI is a raft hydroponic system and the aquaculture part focus is on tilapia production (Rakocy, 1989; Rakocy and Hargreaves, 1993; Rakocy, 1997; Rakocy et al., 1997; Rakocy et al., 2003; Rakocy et al., 2004a; Rakocy et al., 2006a; Rakocy et al., 2006b; Rakocy et al., 2007; Rakocy et al., 2012).

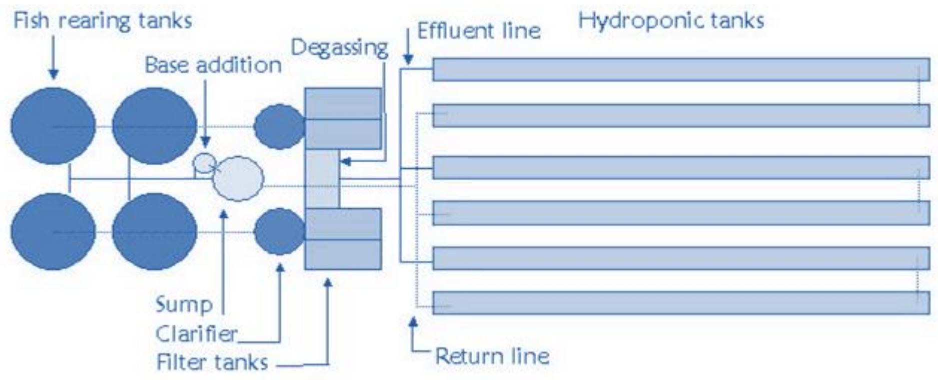

Figure 2.1 UVI aquaponic system diagram (Rakocy et al., 1997)

A continuous operation was run at UVI for 2.5 years (1995-1997) with red tilapia and leaf lettuce production (Rakocy et al., 1997; Rakocy et al., 2007). The system (Figure 2.1) staggered fish production using four fish rearing tanks, each with 7.8 m^3 water volume (total 31.2 m^3), two cylindro-conical clarifiers (3.8 m^3 each), four rectangular filter tanks (0.7 m^3 each) containing orchard netting, six hydroponic tanks (11.5 m^3 each) and a sump (0.6 m^3). The hydroponic tanks were 30.5 m long by 1.2 m wide by 0.4 m deep and had a combined surface area of 214 m^2. Thus, the surface area to fish tank volume was 6.85 m^2/m^3. The water volume was 110 m^3. A 0.5 hp in-line pump moved water at an average rate of 378 L/min from the sump to the fish rearing tanks (mean retention time of water 1.5 h), from which effluent flowed with gravity through the system. Air diffusers were used both in fish and hydroponic tanks through airstones supplied by air from a 1.5 hp blower for fish and 1 hp blower for plants.

The daily fish feed input averaged 12 kg equivalent to 56 g/m^2 plant growing area. The waste water from the fish was only supplemented with potassium (K), calcium (Ca) and iron (Fe) to provide sufficient amounts of the essential nutrients for normal plant growth. Potassium and calcium were supplied as hydroxides, also serving to raise the pH while supplementing these nutrients. These additions were equivalent to 16.1 g KOH, 3.3 g CaO, 13.7 g $Ca(OH)_2$ (more economical than CaO) and 6.0 g iron chelate (10%) per kg of fish feed. The annual production of tilapia was 3,096 kg and the lettuce production was projected to 1,694 cases (appr. 11 tons), or appr. 3.5 tons lettuce per ton tilapia produced and the land use was 0.04 ha, which can be considered being a small to medium scale system.

2.2 Developing units in Europe

Aquaponic systems are being developed in several places in most if not all European countries. Most of the systems are small hobby or research units. In recent years a few semi-commercial pilot units have been put to the test and these systems provide excellent information for the future developments.

The SME **Breen[2] in Hondarribia, Spain** has developed a system of 500 m^2 during the last five years (Figure 2.2) and is expanding to a two thousand square meter production system (Figure 2.3) in Renteria at Tknika[3], the Centre for Investigation and Applied Innovation in VET (Vocational Education and Training). The installations at Tknika will serve as the main hatchery of tilapia for production installations, as research laboratory and as a national and international training facilities in aquaponics.

Figure 2.2 Breen aquaponics pilot unit in Hondarribia, Spain

Breen´s systems have always been run with tilapia production and many different plants have been tested in the systems, including salads, a variety of herbs, tomatoes, peppers and oranges. The aquaponics development at Breen started in 2010 and the company has made several test units built on grow-bed, raft and nutrient film technique (NFT) - see further description of the different systems in Section 3.4 below.

Figure 2.3 Hatching facilities at Tknika

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[2]www.breen.es
[3] www.tknika.eus

Figure 2.4 New 6,000 m^2 commercial aquaponics farm under construction

Breen has associated with an investor group called NER. This alliance is constructing a new aquaponics production unit of 6,000 m^2 to produce up to 125 tons of tilapia, 15 tons of tomatoes, 6 tons of strawberries and up to 50,000 salads per year. The installation is situated close to the pilot unit in Hondarribia and is planned to start operation mid 2016 and be in full production a year later. Photos from the construction site are shown in Figure 2.4.

Institute of Global Food and Farming (IGFF)[4] in Denmark has developed a decoupled aquaponics unit of 60 m^2 (Figure 2.5). The IGFF unit consists of six plant tables arranged in three pairs of 1.45 x 7.50 m on the top of three rectangular fish tanks (3 x 1 x 0.8 m) with a usable volume of 2 m^3 each. Plant tables produce horticulture products in pots with soil and compost to open up for the prospect of getting an organic certification for the aquaponic system. Soil is used because to obtain an organic certification requires plants to be grown in various specified types of soil. Silver

Figure 2.5 IGFF aquaponics pilot unit

[4] www.igff.dk

tilapia, red tilapia and pike perch have been tested as fish species and various plants such as lettuce, basil, tomatoes and peppers have been grown successfully on the plant tables.

Figure 2.6 shows a schematic drawing of the system. Water to the plants is supplied by the “ebb and flow” principle. To secure as much as possible plant growing area in the greenhouse cube, the bio-filter, UV-lighting, air pumps, pH regulation and sedimentation tanks are placed outside the cube (Figure 2.7). The oxygen supply to the fish tanks is secured by three independent air blowers. The tanks are connected to a central water discharge line that ends in two sedimentation chambers. These chambers do not only serve as pre-filtration systems but also as pump sumps. Each chamber is connected to one separate lift pump, providing a pumping capacity of around 15m^3/h. The total water flow is split into two independent loops. In one of them, the fish loop, the pumps supply water to a bead filter that acts as a mechanical as well as a biological filter. This loop has in-line ultraviolet disinfection system (UV system). From the UV system the water can be led to the plant tables and/or directly back to the fish tanks located beneath the plant tables. The water from the plant tables can also enter the fish tanks by gravity or can directly be discharged into the main discharge line and the sedimentation chambers.

In the second loop (plant loop) the lift pump supplies the water directly back to the plant tables from where it enters the fish tanks. Both lift pumps are frequency regulated, and the plant loop pump is equipped with a timer that allows to pre-set pumping time and -duration to follow a “ebb and flow” watering schedule of the plant tables (Kledal, 2012).

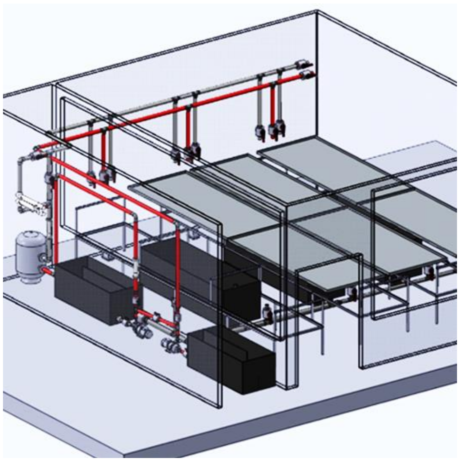

Figure 2.6 Schematic diagram of the IGFF aquaponics pilot unit

Figure 2.7 Bio-filter, UV-lighting, sedimentation tanks and airblower

The Icelandic company Svinna-verkfraedi Ltd[5] has in collaboration with the University of Iceland implemented a RAS system with tilapia in the greenhouses of Akur, an organic greenhouse horticulture farm in South Iceland. The RAS system is connected to an NFT system with okra, tomatoes, beans and lettuce. The fish waste water nutrient solution is also used for irregation of the organic soil production. The aquaponic system consists of three 4 m^3 fish tanks, a drumfilter, a biofilter, a sump tank and NFT pipes for larger plants, see Figure 2.8.

Svinna has developed aquaponic systems since 2013 and has run tests with grow beds, raft and NFT with several other plant types. The setup today is partly decoupled as part of the water is used for soil irrigation and the plan is to move more in that direction to secure optimum conditions for both fish and plants. The company is now adding crayfish to the system to make use of the sludge from the fish tanks. Furthermore, a worm bed is used for plant waste. Thus, zero-waste is obtained in the system. The company aims to link educational and experience tourism to the production showing the water and nutrient cycles, how waste from one production unit is turned into value for the next one and how sustainable geothermal energy is used for the production. The future ideas also include a restaurant serving the products from the system. Moreover, further research is planned for future development and expansion of production.

Figure 2.8 Svinna aquaponics pilot unit in Laugaras, Iceland

[5] www.svinna.is

Nibio[6] **(former Bioforsk) in Grimstad South Norway** has since 2010 been involved in aquaponics development (Skar, 2010). The institute developed and implemented a test system in 2013, based on cold water fish and has tested brown trout and rainbow trout in the RAS system together with salad production in a raft system, see Figure 2.9. The system has been running stable with a weekly production of salad. The system at Nibio includes four 1 m^3 fish tanks and two 15 m^2 raft basins. Mechanical filtration is performed at each tank and through a bead filter which also serves as biofilter. Furthermore, a trickling filter provides additional biofiltration and aeration.

Figure 2.9 Nibio aquaponics pilot unit in Grimstad, Norway

The SME **Ponika**[7] in Slovenia has built a 400 m^2 commercial aquaponic system recently starting up production. The system is situated in the heart of the Landscape Park Goričko and Natura 2000 site. The RAS system has largemouth bass and the plants grown are chives, peppermint, basil and lemon grass in 495 rafts, see Figure 2.10.

Figure 2.10 Ponika aquaponics pilot unit in Prekmurje, Slovenia

[6] www.nibio.no
[7] www.ponnod.com

Eureka Farming[8] in Italy has developed a 500 m^2 experimental area under two greenhouses and outdoor space supplied with floating systems, substrate aquaponics and dynamic root floating technique (Figure 2.11). The company has successfully farmed both freshwater (nile tilapia, largemouth bass, African catfish) and saline fish species (grey mullet, European seabass). Beside the biological production and the quanti-qualitative improvement of the productions from traditional horticulture, the focus of Eureka is to develop new aquaponics solutions for the industry that allow the expansion of aquaponics with both staples and saline crops. Eureka has been committed in bringing aquaponics and integrated systems in arid lands, in designing and running micro systems in South East Asia for food security and to carry out R&D for the integration of the tilapia nursery industry with aquaponics.

Figure 2.11 Eureka farm R&D unit near Rome, Italy

The FishGlassHouse was built at the campus site of the Faculty of Agricultural and Environmental Sciences (AUF), University of Rostock in Germany. The fully closed interval controlled aquaponic system consists of three aquaculture units (300 m^2) and six cabins for plant cultivation under hydroponic conditions (600 m^2). The fish production of African catfish (*Clarias gariepinus*) is carried out by using juveniles from a local fish producer (PAL Anlagenbau GmbH, Abtshagen). Different plants like herbs and vegetables are produced within the different hydroponic subsystems. Experiments are carried out under floating raft, "ebb and flow", nutrient flow technique (NFT) or planting table conditions in cooperation with a local plant producer, Grönfingers GmbH (Rostock).

Figure 2.12 FishGlassHouse

[8] www.eurekafarming.com

The University of Applied Sciences (ZHAW)[9] in Switzerland has conducted research and development of aquaponics for several years (Graber and Junge, 2009). This has resulted in the spin-off company **UrbanFarmers**[10] developing rooftop and bolt-on aquaponic systems internationally. An aquaponic research and training facility of 292 m^2 has been built at ZHAW in Waedenswil and a 260 m^2 system has been built at UrbanFarmers in Basel (Graber et al., 2014a; Graber et al., 2014b). This team has been involved in development of the Aquaponic system in Naklo, Slovenia (Podgrajsek et al., 2014).

Tropenhaus[11] in Switzerland operates two tropical greenhouse sites with coproduction of fish and plants, in Frutigen with sturgeon and in Wolhusen with tilapia. In both cases visitor centres are a large part of the business concept with exhibitions and tours, meeting facilities, shops and restaurants offering a taste of the products in a tropical environment. A Tropenhaus facility has also been built in Germany[12].

More European startup companies within aquaponics can be mentioned[13,14] but in general the systems are still small or in the designing phase. The EU funded project **INAPRO**[15] (2014-2018) led by Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB) in Berlin, Germany and including 18 partners from 8 countries will implement four large-scale (each 500 m^2) demonstration facilities in Spain, Belgium, Germany and China.

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[9] www.zhaw.ch
[10] www.urbanfarmers.com
[11] www.tropenhaus.ch
[12] www.tropenhaus-am-rennsteig.de/
[13] http://www.ecf-farmsystems.com
[14] http://bioaquafarm.co.uk
[15] www.inapro-project.eu/

2.3 Decoupled systems

In recent years recirculating aquaculture system (RAS) technology has been developing rapidly in Europe. The water reuse in modern RAS can be 95%-99% (Dalsgaard et al., 2012), with water usage down to below 100 L/kg of fish produced (Martins et al., 2010). This new technology together with new environmental criteria for sustainable aquaculture has led to increased interest in aquaponics within aquaculture businesses. As traditional aquaponics combines fish and plant production in one simple circulation, and thus the same environment, some compromise is necessary to obtain optimal growth for the system as a whole unit. New ideas on decoupled aquaponics involve plans for the physical separation of the fish and plant subunits in two recirculating loops. This is described as decoupled systems, where optimal condition for each system is applied with periodic water exchange between the two subunits. Decoupled aquaponic systems are believed to provide key steps towards the breakthrough of large-scale commercial aquaponics. Additionally, decoupled systems offer a level of risk mitigation that a balanced system does not. In the instance of a fish or a plant pathogen problem, each subunit can be isolated.

IGFF has constructed the aquaponic pilot unit by having a double loop and thus can run the system totally or partly decoupled. Figure 2.12 shows photos from IGFF under construction.

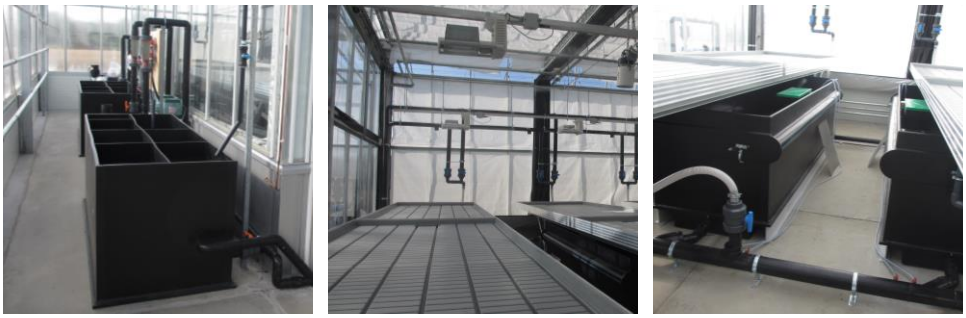


Figure 2.13 Decoupled system at IGFF

Other aquaponic systems such as at Breen, Nibio and Svinna can also run the RAS and hydroponics part separately by simple adjustments. At Svinna a special nutrient water tank for the organic plant part growing in soil is using waste water from the RAS part without returning the water. The hydroponics part could be connected to this system or a special nutrient water tank collecting waste water from the RAS system. The nutrient concentrations, pH, temperature etc can then be adjusted for the plants.

3 System description

3.1 Recirculating aquaculture system (RAS)

Recirculating aquaculture systems (RAS) have gained increasing interest in recent years as they reduce the water use through circulation and thus use only a small percentage of water compared to traditional flow through systems. Therefore, the environmental impact can be minimized while intensifying fish production in a controlled environment. To maintain good water quality the water has to be filtered to remove solids, ammonia and CO_2. Likewise the dissolved oxygen level, pH and temperature have to be kept at secure levels at all times. The RAS technology has been developed in recent years, especially in relation to sludge handling and biofiltration (Dalsgaard et al., 2012). The RAS technology development, together with more stringent environmental requirements and the need to increase profitability, have led to increased interest in integrated multitrophic production methods such as aquaponics, which converts the RAS water treatment costs for biofiltration into profit by growing plants that take up nutrients and help to control ammonia from the fish tanks. A schematic overview of RAS is shown in Figure 3.1.

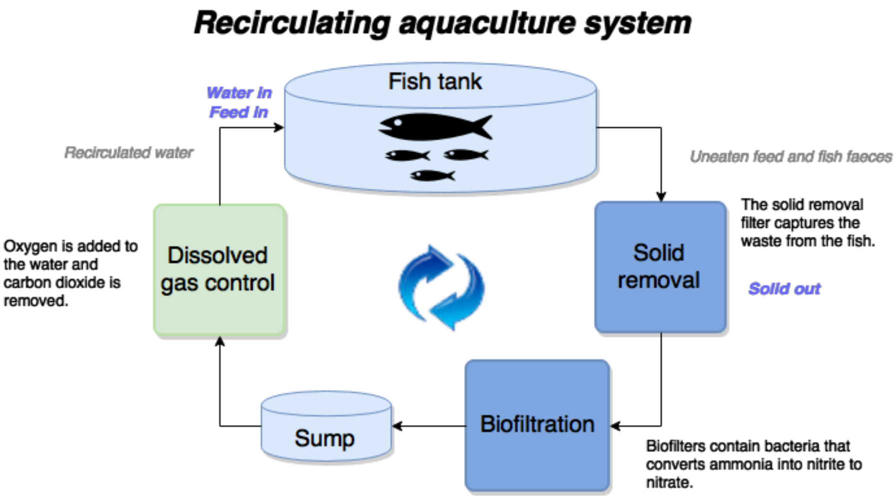


Figure 3.1 Schematic overview of a recirculating aquaculture system (RAS)

3.2 Mechanical filtration

Fish feed and excrement solid removal is a fundamental step in every RAS in order to keep good water quality and to prevent the system from failing. Not only does waste increase the risk of fish disease and gill damage, but also increase the ammonia in the water, decrease the oxygen concentration due to higher biochemical oxygen demand (BOD), reduce the biofilter efficiency by fouling the media with heterotrophic bacteria, and favour clogging that lead to the formation of anaerobic spots that release hydrogen sulphide, an extremely toxic gas for both fish and nitrifying bacteria.

The first goal in solids removal is to reduce the retention time of solids in the system as much as possible. The sooner solids are separated from the main system, the less chance there is that solids break down into smaller particles, making them more difficult to treat, or consume oxygen. Thus, mechanical filters are in general put after fish tanks and before the biofilter to remove solids originating from uneaten feed and fish faeces.

In aquaponics it is very important to include effective filtering of organic solid. It is estimated that ineffective solid waste removal has led to more than 85% of failed aquaponics systems. If the solids are not removed they will have negative impact on the plants by clogging the roots, and the substrates in media systems which increase the system oxygen demand and the risk of hydrogen sulphide and methane generation. Filtration of fish waste water for aquaponics has been found to significantly increase lettuce yield (Sikawa and Yakupitiyage, 2010).

Dalsgaard and Pedersen (2011) measured all solid and suspended/dissolved waste from a rainbow trout RAS farm. On average, they found 48% of the ingested N recovered in the water, total ammonia nitrogen (TAN) constituting 64–79% of this, and 7% in the solids. In comparison, 1% of the ingested P was recovered in the water and 43% in the solids. This emphasises the need for using the solid waste as this is a valuable souce of nutrients. Further research for recovering phosphorus and other resources from RAS wastes is ongoing (Zhang et al., 2013). Some trials carried out at the University of the Virgin Islands have proved that composted fish solids are a valuable substrate for the nursery of plants or for substrate hydroponics due to their release of mineralized nutrients (Danaher et al., 2011; Pantanella et al., 2011a). The same team conducted a preliminary evaluation of solids digestion, evaluating the time it takes for solids to mineralize or release usable dissolved nutrients that were bound in the discharged solids from their aquaponic system (Rakocy et al., 2005). In Canada Dr. Nick Savidov‘s research cluster has been focusing on the mineralization of the fine fraction of solids within the aquaponic system, with the objective of increasing the nutrients available to plants through increased mineralization.

Mechanical filtration can be accomplished in many ways. Normally filtration methods rely on gravity (sedimentation, swirl separators/radial flow separators), screening (microscreen (drum) filter, sand filter, bead filter), oxidation (ozone treatment) or foam fractionation. It is of great importance to secure operation of mechanical filtration units at all times and to take care of the sludge that is removed from the system.

All the different options available have their advantages and disadvantages. A good overview of basic information is presented in Recirculating Aquaculture by Timmons and Ebeling (2010) or Aquaculture Engineering by Lekang (2013).

In summary, mechanical filtration techniques relying on gravity require a large surface area and manual cleaning/purging; they are only efficient at removing large settleable particles (>100µm) but are generally simple and cheaper to construct. Filtration techniques relying on screening often require more complicated equipment, including (automated) backwash features; they can be more expensive to buy but require much less floor space and are generally self-cleaning.

For sedimentation basins (Figure 3.2 left), radial flow separators and swirl separators it is important to design the filter in such a way that all turbulence inside the filters is avoided. Any turbulence, such as sudden change in water velocity will resuspend the solids and reduce filter efficiency. An additional disadvantage of these filters is that solids remain in the system´s water, where it promotes growth of heterotrophic bacteria that can consume large amounts of oxygen.

Drum-filters (Figure 3.2 right) with automatic backwash in contrast will remove solids within minutes from the system water which allows for separate treatment (e.g. mineralization/digestion) and reduces oxygen consumption in the system. Drum-filters require a high-pressure pump for backwash and periodic servicing but are generally highly automated. Screen sizes between 10µm – 500µm are available but normally screens in the range of 40µm-80µm are used.

Figure 3.2 Sedimentation tank (left) and drum filter (right)

Sand filters have been in use for a long time. Due to the small pore sizes between grains of sand they provide very good removal efficiencies (down to 5µm) and water quality. This small pore size also means that a high pressure is needed to pump water through, generally between 1.5-3 bars. Bead filters require bigger plastic beads which cause much less resistance but also a slightly lower filtration efficiency. Good bead filters (without six-way valves) normally can be run using low-head energy efficient pumps. Both bead filters and sand filters have the disadvantage that solids are also kept in the system water until they are purged (manually or automatically) from the filter.

For the removal of fine solids (<30µm) a protein skimmer or foam fractionator might be used as well. These filters rely on agitation of water to create floating foam to which fine suspended solids bind and which is then removed from the water via a foam trap. Foam fractionators are often used in salt water systems but can also be used in fresh water, albeit with lower efficiency.

The choice between passive sedimentation and mechanical filtration depends on the degree of intensification of the farm. The smaller the farm and the volume of water to be treated the more convenient it is to use the sedimentation options due to the lower costs and lower maintenance, providing that an adequate retention time of water in the settling tank is maintained. The intensification of production (high fish stocking densities and higher feed rates), the higher volume of water and the choice of more sensitive species make the use of drum filters more convenient. The most important thing is to secure their operation at all times and to take care of the sludge that has to be promptly removed from the system. Because these filters are so effective at removing solid waste from the system, they are quickly eliminating nutrients from the system and plant nutrient deficiencies may appear. Discharged effluents from the drum filter are thus often digested in a separate loop and dissolved nutrients returned to the system. Table 3.1 compares the relative cost and the pros and cons of different mechanical filtering systems.

Table 3.1. Comparison of different mechanical filter systems.

Type	Op. water volume (m^3/h)	Op. pressure (PSI)	Cost (€)	Pros	Cons
Clarifier	5	Atmosph	1000	Maintenance-free. No electricity, requires only purging the system from sludge.	Low water volume compared to alternatives. Water retention time depends on the particle size to be removed.
Swirl sep.	17-34	Atmosph	1200	Maintenance-free. No electricity, requires only purging the system from sludge.	Low water volume compared to alternatives. Water retention time depends on the particle size to be removed.
Bead filter	1) 10 2) 23 3) 45 4) 68	10 20	1) 3000 2) 8050 3) 12000 4) 20000	Simple operations, limited space for water treatment. Suitable for small or medium farms.	Requires electricity, some maintenance needed, beads may need to be replaced. Water needed for backflush with relative disposal. Number of flushes depend on the solid load.
Sand filter	1) 10 2) 22	30-50	1) 700 2) 1200	Simple operations, limited space for water treatment. Suitable for small or medium farms.	Requires electricity for pumping, not practical with organic wastes, as particles foul on sand making clogs. More frequent backflush.
Drum filter	1) 30 2) 90 3) 140	Atmosph	1) 5200 2) 7000 3) 9000	Effective for big farms. Water movement is by gravity.	Requires electricity, some maintenance needed, screens need to be periodically replaced. Water needed for backflush with relative disposal. Number of flushes depends on the solid load and the mesh of the screen.

3.3 Biofiltration

Biofilters are a prominent feature in recirculating aquaculture and in aquaponic systems. The water is treated by converting dissolved ammonia, a toxic metabolite excreted by fish, into harmless nitrate. This conversion, operated by beneficial bacteria, is the main reason for the huge water saving obtained by RAS, since it avoids the discharge/replenishment of water normally occurring in traditional systems to keep ammonia concentrations below toxic limits for fish. A healthy and matured biofilter is crucial for a stable and well working RAS (Timmons and Ebeling, 2010). There are mainly three nitrifying bacteria species taking part in the conversion: *nitrosomonas* convert ammonium to nitrite and *nitrobacter* and *nitrospira* convert nitrite to nitrate. These bacteria are naturally occurring in our environment. They are very effective aerobic autotrophs using ammonium and nitrites, respectively, as energy source. However, they need a surface to colonize e.g. gravel, pumice and/or plastic material. This bacterial substrate needs to have a high surface area.

A biofilter is typically a canister, tank or barrel of some sort that holds a porous media, bacteria and well aerated water. It can be a very simple setup or industrially complex. After effective solids removal the water runs through the biofilter where the ammonium is efficiently converted to nitrite and then to nitrate. The bacteria on the biofilter are not visible and are not readily measured outside of laboratory conditions. Therefore, the best way to determine whether it is working is to constantly monitor the levels of ammonium, nitrite and nitrate.

An acclimation period is required to start up any new system. During this time of beneficial bacterial establishment operators must monitor ammonia and nitrite closely to avoid lethal levels. Each fish species has unique tolerances to these parameters. The startup of a new biofilter can take as long as six weeks depending on environmental conditions (e.g. temperature, dissolved oxygen, pH or salinity). Initially ammonia levels will rise until the nitrosomonas bacteria colonize the system. At this time ammonia will begin to decline. As ammonia declines it is converted to nitrite and a corresponding rise in nitrite levels will be observed. Once the nitrobacter/nitrospira bacteria have established, nitrite levels will decline resulting in production of nitrates. Once nitrates are produced and ammonia and nitrite levels remain low the system can be considered acclimated and ready to feed at maximum capacity of the designed system. There are methods of speeding up the acclimation of a new system including dosing the system with ammonia before fish are introduced, then monitoring for the trends in ammonia, nitrite and nitrate. Another method is to seed or inoculate a new system with cultured water from an already established system.

Nitrate is relatively harmless to the fish and is the primary nitrogen source for the plants. From the overall chemical processes shown below, it can be noticed that hydrogen ions are released meaning that the pH of the system will be lowered, depending on the buffer capacity of the system. The progressive consumption of alkalinity due to the continued release of hydrogen ions needs to be properly balanced by the constant supply of bases in the form of carbonate ions (calcium carbonate), bicarbonate ions, or alkali (calcium hydroxide, potassium hydroxide). It should also be noted by the equations below that the nitrification process is also oxygen consumptive. The beneficial bacteria rely on a constant supply of oxygen to operate efficiently.

Nitrosomonas converting ammonium to nitrites:

$$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + 2\ H^+ + H_2O$$

Nitrospira/Nitrobacter converting nitrites to nitrates:

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^-$$

The overall reaction for ammonium conversion to nitrates is:

$$NH_4^+ + 2\ O_2 \rightarrow NO_3^- + 2\ H^+ + H_2O$$

RAS is a dynamic system, fish are constantly producing ammonia and excreting it into the water. Ammonia is transported into the biofilter and converted into nitrate. In a healthy system the concentration of ammonia is always within non-toxic levels for the fish. Nitrite, the product of the first step of ammonium conversion, is also toxic to fish. Hence, both bacterial colonies must be fully functioning.

The size of the biofilter depends on several factors (Chen et al., 2006). Those are:

- Temperature
- Water salinity
- Oxygen concentration in water
- Surface area of filtration media
- Water exchange rate in the biofilter tank
- Fish stocking density and feeding regime
- Protein content of the feed

Many biofilter options exist and performances depend on the technology and the characteristics of the media. Common biofilters in use are (see Figure 3.3):

- Bead filters - biofilter media is contained in a pressurized chamber. Beads are periodically stirred to clean the media from accumulating dirt that is removed through backflush.
- Sand filters - the media is contained in a pressurized chamber and is agitated. The higher specific surface of sand allows for very high nitrification rates.
- Trickling filters - can be used with different media having various specific surfaces such as plastic beads, gravel or clayballs. Water is sprinkled on top of the canister allowing nitrifying bacteria to grow on the water-air interface of the media. Trickling filters provide a passive aeration and carbon dioxide removal.
- Moving bed bioreactors (MBBR) - neutrally buoyant beads or biomedia are kept agitated in water by means of aeration or stirring. Aeration keeps water oxygenated and removes carbon dioxide from water.

In aquaponics the use of media beds for the plants bring additional biofiltration capacity, which make the systems more resilent to ammonia peaks.

Figure 3.3 Bead filter, trickling filter, moving bed bioreactor and swirl separator

Beside the passive aeration occurring in biofilters water needs to be adequately and constantly aerated to provide sufficient oxygen for plants, fish and the microbial community. The amount of oxygen required depends on the species being reared, on the fish density and the feed supplied to the animals.

3.4 Hydroponics

Hydroponics is a soil-less horticulture method of growing agricultural crops. Various substrates provide plant support and moisture retention. Within these media options, irrigation systems are integrated, providing a nutrient-rich solution to the root zones. All the necessary nutrients for plant growth are supplied by this solution. There are several designs of hydroponic systems, that might serve different purposes, but all have those mentioned basic characteristics.

Aquaponics uses the system design of hydroponics for growing plants. There are three main aquaponics techniques widely in use worldwide; media beds, floating rafts or deep water culture (DWC) and nutrient film technique (NFT), see Figure 3.4. The media beds utilize various substrates in an “ebb and flow” process while in the NFT (in thin layer of water) and raft/DWC systems (floating rafts in large water tanks) the plant roots grow directly into the water.

These systems can all work well, nevertheless they all require effective mechanical filtering to avoid fish waste accumulation on the plant roots. In small scale aquaponics the media-based systems are often used for both mechanical filtration/solid removal and biofiltration. This may work well for very low stocking densities (below 10 kg/m^3) or with feeding regimes of 15-20 g/m^2/day. Organic waste tends to accumulate if these systems are not properly managed and they eventually need to be cleaned to maintain a healthy environment for both fish and plants. In these lightly fed systems, worms are often introduced to the media bed to process solids that may otherwise accumulate leading to anaerobic zones within the bed. NFT and DWC systems are convenient for smaller plants as salad, greens and herbs and can be used for larger plants as well. The NFT system is probably the easiest system to operate in large commercial scale operations, especially for leafy vegetables with a fast turnover, as it is easier to handle and to clean the system between batches and it requires much less water pumping. Lennard and Leonard (2006) did comparison tests on media bed, raft (DWC) and NFT for lettuce production in aquaponic systems and the results showed significant less growth in NFT. On the other hand successive studies carried out in Italy showed that NFT performed as well as DWC providing that adequate nutrients levels and water flow are maintained in the troughs (Pantanella et al. 2012).

Figure 3.4 From left: Media bed, nutrient film and floating raft aquaponics

3.4.1 Grow beds

Figure 3.5 Grow-beds at Breen

Grow beds (Figure 3.5) are often used in different backyard aquaponic systems and are perhaps the simplest and most used technique for small scale systems. It is a solid media-filled bed system, filled with e.g. gravel, expanded clay or pumice that provide additional surface for biofiltration/nitrification, mineralization and thus efficient plant growth. Grow beds simplify the management tasks for unexperienced aquaponists because the additional nitrification occurring in the media reduce the risks of ammonia peaks due to fish overstocking or overfeeding. The grow bed is periodically flooded and drained with water from the aquaculture. The "ebb and flow" of water and air allows the media to "breath" and to meet the needs of nitrifying and heterotrophic bacteria that use oxygen, water and dissolved wastes to mineralize and free nutrients for plants. Media bed systems are often used to remove solids under very low fish stocking densities. For long-term operations, higher fish densities and feeding regimes, a dedicated solid removal unit is needed. If the fish to plant ratios are too high thus bringing amount of wastes above the bacterial capacity to mineralize them, the grow beds start to accumulate organic matter and can eventually clog leading to toxic anaerobic conditions followed by the production of hydrogen sulphide and methane, which can kill both fish and plants. Nitrifying and heterotrophic bacteria are a vital part of the grow bed, moreover, worms can be added to enhance the break-down of organic materials (vermi-compost). The grow bed is excellent for fruity plants such as tomatoes and cucumbers, due to the mechanical support provided for the roots of the plants but can also work well with strawberries and leafy vegetables.

3.4.2 Nutrient film technique (NFT)

Figure 3.6 Nutrient film technique with okra plants

The nutrient film technique (NFT) system (Figure 3.6) is based on growing plants in long narrow plastic channels with a thin film of water continuously flowing through. The NFT system needs good preliminary mechanical filtering systems, as accumulation of solids on the roots needs to be avoided. An aquaponic NFT system mainly follows the same technique of hydroponics, with preferably flat-bottomed channels positioned at 1% slope and a water flow regime of 1-2 L/min. Given the small volume of water channels must not be longer than ten meters to avoid oxygen depletion by the roots. NFT systems are suitable for smaller plants such as salad and herbs and may even be used for larger plants including tomatoes and okra. NFT is a popular option for small hobby systems and good looking show cases. They are also excellent for large scale production units. The pipes are easy to maintain and clean between batches and the system requires much less energy for pumping very small volumes of water if compared with DWC and grow bed systems. Nonetheless, there are issues with NFT systems such as the decrease of the water‘s nutrient content towards the pipe‘s outlet. This can be solved by increasing the flow of nutrients delivered into the pipe. Root clogging and potential high temperature nutrient solutions can also result using NFT. Extra precautions should be taken to ensure a reliable source of backup power. Without water-flow roots can quickly dry out killing plants.

3.4.3 Raft / deep water culture (DWC)

Figure 3.7 Floating system / deep water culture (DWC)

The raft system also known as deep-water culture (DWC) (Figure 3.7) is used for small as well as large aquaponic systems. Tanks are in general 30 cm deep filled with water and with plants floating on plastic sheets accessing the water through openings. The plant´s roots grow directly into the oxygenated water continuously flowing from and to the fish tanks with a volumetric exchange rate of approximately 30% per hour. The leaf crop management typically consists in the transplanting of 3-week old seedlings growing on media cubes in each of the openings of the raft, at one end of the tank. The plants are then harvested at the other end of the tank following a conveyor movement of the rafts that are movable on the water. This provides a space-efficient and productive system ideal for large scale systems. The DWC is very stable as plants can withstand temporary power outages due to the consistent volume of water available containing both oxygen and nutrients. This technique shows some challenges in providing a stable and clean system due to organic sediments (fish wastes, crop wastes, biofloc precipitates) settling at the bottom, which require an efficient mechanical filtering to process fine particles in an optimal way. Lack of proper solid waste management would result in sludge accumulation on the plant roots, starving them from oxygen and the uptake of N-nutrients.

4 System control and optimization

Maintaining good water quality within aquaponic systems is fundamental to the well-being, sustainability and success of the system. Water quality is a broad term encompassing anything that adversely affects the conditions required for maintaining healthy fish and plants. Therefore, requirements for maintaining water quality can vary in different parts of the aquaponic systems. It is necessary to understand the water conditions required in each part of the system and how they affect other parts of the aquaponic system so that these parameters can be monitored and adjusted when necessary to maintain a well-balanced system. For large scale aquaponics it is necessary to maintain a healthy environment for fish, plants and bacteria continuously to obtain good quality and optimal production from each sector. Thus, it is necessary to implement good management practices and system control, including automatization and necessary alarms. The main parameters and their control are described in the following Section.

4.1 Controlling environmental parameters

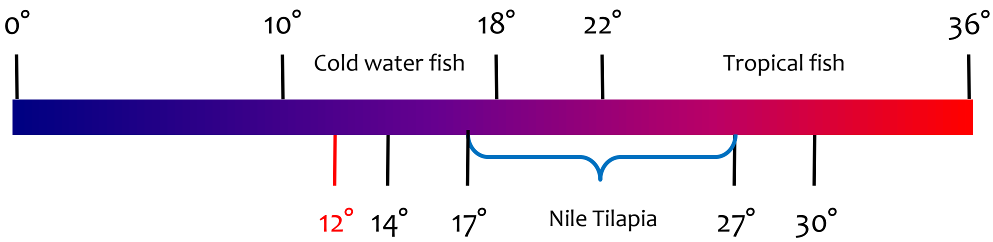
The water in aquaponics is the life-blood of the system. It is the liquid medium through which all essential macro- and micronutrients are transported from the aquaculture to the hydroponics component of the system, and the medium through which both the fish and plants receive oxygen. Thus, water is one of the most important medium to understand in an aquaponic system. There are plenty of parameters involved, but five key water quality parameters are of special importance to follow closely and even with online monitoring: dissolved oxygen (DO), water acidity (pH), water temperature, nitrogen compounds and electrical conductivity (EC) of the water. Each parameter has an impact on the unit’s organisms i.e. fish, plants and bacteria. Each organism has an ideal parameter range for optimal growth.

Other water parameters are necessary as well but can be measured once a week or even once a month or more seldom in well balanced and stable aquaponic systems. These include phosphorus and other macro- and micronutrients, carbon dioxide and total dissolved solids.

On-line monitoring of temperature, pH, ammonia, DO and EC can be undertaken by simple and relatively inexpensive aquarium control systems e.g. from Profilux or more expensive industrial equipment e.g. from Hach, Oxyguard or Priva, related to the size and design of the system. Aquarium kits for measuring e.g. ammonia/ammonium, nitrite, nitrate and phosphate are quite accurate and cost efficient. For more accurate measurements spectrophotometers such as from Hach or Hanna Instriuments or portable multifunction probes can be used for most parameters.

4.2 Temperature

Each fish species and plant type has a preferred temperature range that should be researched for optimum fish growth, bacterial activity and plant production. Generally, tropical fish thrive at 22–32°C while cold water fish prefer 10–18°C. With respect to *Oreochromis niloticus* (Nile tilapia) their vital range lays between 14-36°C (they do not feed or grow below 17°C, and die below 12°C) and the optimal growth range is between 27-30°C. The latter allows the best growing performance; i.e. a grow-out stage of 600-800 grams in 6 - 8 months (Timmons and Ebeling, 2010). Additionally, optimal temperatures (and consequently less stress) reduce the risk of diseases. Thermal isolation, heat exchangers, water heaters and coolers help to achieve a steady temperature level, however, these means may be costly in areas and/or countries where energy/electricity is expensive. It is thus often better to grow fish adapted to local environmental conditions. Plants also have different temperature requirements, e.g. 15-19°C for salads while tropical plants need higher temperature and humidity.



The acceptable temperature range for nitrifying bacteria is 17–34°C. This range encourages growth and productivity. In particular, the *Nitrobacter* group is less tolerant with respect to lower temperature compared to the *Nitrosomonas* group, and as such, during colder periods nitrite should be more carefully monitored to avoid harmful accumulations.

4.3 Dissolved oxygen

Oxygen is essential to the survival of fish in all aquatic systems. The solubility of oxygen decreases with rising water temperature and increasing salinity. Oxygen is measured as dissolved oxygen (DO) and it is possibly the most important water quality parameter in an aquaponic system. To obtain good fish growth, DO levels should be maintained at saturation and at least above 5 mg/L. Low dissolved oxygen levels are responsible for more fish kills in aquaculture, either directly or indirectly, than all other problems combined (Lennard, 2012). Oxygen consumption is directly linked to size, feeding rate, activity level, system cleanliness from wastes and temperature; large fish consume less oxygen than their smaller counterparts, which have higher metabolic rates. Warm water species, e.g. tilapia, may better adapt to the occasional low DO levels than cold water species. All species can tolerate adverse condition for short periods, provided that such occurrences are infrequent. Low DO can though cause potentially irreversable damage to gills and reduce the efficiency of the nitrifying bacteria.

4.4 Chemical oxygen demand and biochemical oxygen demand

The chemical oxygen demand (COD) and the biochemical oxygen demand (BOD) are measures of the amount of organic matter in the system that use up dissolved oxygen, therefore, high CODs and BODs are not desirable, especially for fish health. Both of these parameters are measured using laboratory methods and performed less frequently e.g. once, or a few times a year. COD and BOD can be kept low by maintaining effective filtering of solids in the system and regular cleaning of tanks and pipes.

4.5 pH

Water acidity (pH) is known as the master variable in aquaponics because it influences many water quality parameters, including % NH_3 vs. % NH_4^+ available as well as the solubility of other plant nutrients which affects both fish and plants. As a measure of acidity, pH is presented on a logarithmic scale from 0-14 where pH 0<7 is acidic, 7 is neutral, and 7<14 is basic. The pH of a water system represents the amount of hydrogen ions - also referred to as a measure of the hydrogen ion activity (H^+) of the water.

$$pH = -\log(H+)$$

The equation shows that as the hydrogen ion activity rises, the pH is lowered. This means that acid waters have high levers of H^+ and hence low pH.

Temperature and pH affect the total ammonia nitrogen (TAN) of the water: e.g. at pH 4.5 nitrification has ceased and TAN concentrations increase.

$$NH_4^+ \xleftarrow{decreasing\ pH} \xrightarrow[increasing\ pH]{} NH_3$$

ammonium ion (less toxic) unionised ammonia

The acceptable range for fish culture is usually between pH 6.5 to pH 9.0. When water is very alkaline (>pH 9), ammonium in water is converted to toxic ammonia, which can kill fish, on the other hand, acidic water (<pH 5) leeches metals from rocks and sediments (and solid substrates in grow beds). These metals have an adverse effect on the fishes' metabolism rates and ability to take in water through their gills, and can be fatal as well. Aquaculture pH guidelines for warm water fish suggest that: pH<4.0 is acid death point; pH 4.0 – 5.0 there is no production, pH 6.5 - 9.0 is a desirable range for fish production, pH 9.0 - 11.0 gives slow growth, and pH> 11.0 is the alkaline death point (Lawson, 1995; Tarazona and Munoz, 1995). Importantly, different fish species can be more tolerant to changes in pH. For example, tilapia can tolerate a wider pH range, pH 5.0-10.0, but other species may not.

Plants prefer pH< 6.5 and nitrifying bacteria perform optimally at pH> 7.5. Usually pH is one of the water quality parameters that the optimum value for fish does not match with the optimum pH for plant growth (Rakocy et al., 2004a). This remains one of the challenges of the simple aquaponic systems: to balance the fish pH to the particular plant pH requirements. Based on these data the highest possible pH value should be consistent with the prevention of toxic NH_3 accumulation in the aquaponic system. Consequently the ideal pH value for the system ranges often between pH 6.8 and pH 7.0. Bases such as calcium carbonate, calcium hydroxide and potassium hydroxide may be added to increase pH and maintain pH close to neutral (pH 7.0).

Important:
Great care must be taken when adding base to the system as a large amount of base in a single dose will shift the majority of TAN into the toxic form (NH3) and kill all the fish. It is therefore recommended to add base very slowly over a period of several days.

The pH level needs to be monitored frequently: at least once per week or more frequently. Daily monitoring is suggested as pH generally declines on a time scale of one day as a result of nitrification and respiration. There are several online systems designed for continuous monitoring of pH.

Nitrification produces weak concentrations of nitric acid due to the release of hydrogen ions during the oxidation of ammonia to nitrate. This continuous release brings the aquaponic system to progressively consume alkalinity and become acidic.

Fish respiration increases CO_2 levels in the water, which leads to lowering of pH. CO_2 is also a product of the nitrification, since 5.02 g of carbon dioxide are formed per each gram of ammonia nitrogen. CO_2 build-up in diffuse aeration systems is less frequent as it vent off to the atmosphere. Also, CO_2 levels should not exceed 20 mg/L because at higher levels the fish become sluggish and cannot absorb enough oxygen through their gills.

4.6 Alkalinity

Alkalinity is linked to pH. Alkalinity as $CaCO_3$ equivalents is the sum of the carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ion equivalents. It represents the ability of a water system to neutralize acid in the water without changing its overall pH level. Alkalinity is a key parameter that should be measured once per week to once per month, depending on the size of the aquaponic system and fish stocking density. Maintaining alkalinity >100 mg/L as $CaCO_3$ is recommended. The correct pH, alkalinity and hardness (high content of dissolved ions - sometimes referred to as high mineral content) are known to be essential for a successful pond fertility aquaculture programme. Alternately adding calcium carbonate, calcium hydroxide and potassium hydroxide from a base addition tank is suggested for correcting pH when it is dropping (towards acidic). Hydrogen ions from nitrification are neutralized by hydroxides (OH^-) from completely dissociated strong alkali, or react with the carbonate or bicarbonate ions to form carbonic acid (H_2CO_3) which is a weak acid. This results in the pH increasing once more towards a more neutral pH. The buffering capacity in intensively run RAS and aquaponic systems is quite high, because each gram of ammonia nitrogen consumes 7.02 grams of alkalinity (as $CaCO_3$) during the nitrification.

In summary alkalinity is the sum total of components in the water that tend to elevate the pH of the water above a value of about 4.5. It is measured by titration with standardized acid to a pH value of about 4.5 and it is expressed commonly as milligrams per liter of calcium carbonate. Alkalinity, therefore, is a measure of the buffering capacity of the water, and since pH has a direct effect on organisms as well as an indirect effect on the toxicity of certain other pollutants in the water, the buffering capacity is imperative for water quality. As stated above carbonates and bicarbonates, which commonly occur in natural waters, increase the alkalinity. Also affecting the alkalinity are phosphates and hydroxides.

4.7 Nitrogen compounds

Nitrogen is one of the critical water parameters. It is part of all proteins and is required by all known life species. Nitrogen enters the system from the fish excrement – and thus indirectly from the feed. A typical protein content in feed for tilapia is 30-32%; whereas carnivore cold water species require a higher protein percentage appr. 50% (Jokumsen and Svendsen, 2010). The proteins result in fish growth and have a high impact on the feed conversion ratio (FCR), the remainder is released as solid and liquid fish waste (Timmons and Ebeling, 2010). The liquid fish waste is mainly released via the gills or the fish's urine in form of ammonium (NH_3 or NH_4^+, depending on the pH of the system). The solid waste that is released into the water in the form of fish excrements (faeces) or uneaten feed, are converted into ammonium by microbes. The extent of this conversion depends on the system design and the degree of microbial activity. NH_3 and NH_4^+ are then nitrified by the bacteria, as explained in the biofiltration Section 3.3 above and in Figure 4.1. The sum of nitrogen from NH_3 or NH_4^+ is called total ammonium nitrogen (TAN). It is recommended to keep TAN as low as possible and below 3 mg/L. Ammonia (NH_3), which is the unionized form of TAN mainly occurring at high pH, is toxic to tilapia at 1 mg/L. Nitrite is toxic to tilapia at 5 mg/L and should also be kept as low as possible. Although ammonia and nitrite (NO_2^-) are approximately 100 times more toxic to fish than nitrate (NO_3^-), the latter can also be harmful to fish at specific concentrations. These depend on the fish species used and the duration they are exposed to the respective concentration. Tilapia is in general a hardy fish and it can easily widthstand concentrations of 100 mg/L or more. All four forms of nitrogen (NH_3, NH_4^+, NO_2^-, NO_3^-) can be used by plants and stimulate growth (Seawright et al., 1998) however the form quickly absorbed by plants is nitrate.

The frequency of measurement should be weekly to monthly for nitrate and nitrite (more frequent if there are problems in supplying DO), but monitoring of TAN should occur on a weekly basis, or more often depending on the environmental conditions, feeding regime and the fish stocking density.

Nitrate is the common form of combined N found in oxygenated waters and can be biochemically reduced to nitrite, which can be rapidly oxidised to nitrate once more (denitrification (nitrate reduction) / nitrification (oxidation of ammonia or ammonium to nitrite)). Natural concentrations of nitrates in rivers are usually less than 0.1 mg/L but may be enhanced by anthropogenic sources. Nitrate and nitrite concentrations typically range between 0–20 mg/L N (Robards et al., 1994) and 1-100 µg/L N (Chapman, 1998), respectively. However, in cases of extreme pollution, concentrations may be as high as 1 mg/L NO_2-N such as in waters strongly influenced by industrial effluent, or 500 mg/L NO_3-N in areas of high N fertilizer application (Chapman, 1998).

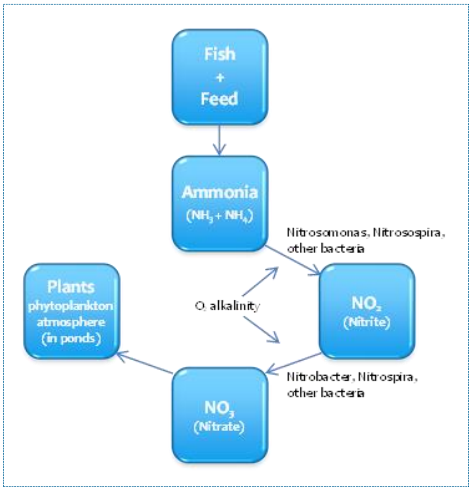


Figure 4.1 Schematic representation of the N cycle in aquatic system

The possibility of overfertilization/overnitrification of waters leading to algal blooms can occur, if nutrient such as nitrate and phosphate are high. This is termed eutrophication and refers to the enrichment of waters by inorganic plant nutrients which results in the stimulation of an array of symptomatic changes. The most common effects are reduced DO levels because of the high BOD of these blooms, leading to mortality of the fish/aquatic life. These consequences are far-reaching and can compromise ecological, social and economic functions of the involved waterbodies (Chapman, 1998; Smith et al., 1999; Withers and Muscutt, 1996).

4.8 Electrical conductivity

Another very important characteristic of the nutrient solution used in hydroponics is the electrical conductivity (EC) measuring the concentration of total dissolved solids. The EC is easy to measure and a good guide, nonetheless, it should be noted that EC can be lower in aquaponic systems compared to numbers given in hydroponics guidelines.

4.9 Macro- and micronutrients

Plants within the aquaponic system need several nutrients that are required for the enzymes that facilitate photosynthesis for both growth and reproduction. Usually, these nutrients can be taken up from soil. As hydroponics is a soil-less cultivation method, these nutrients have to be supplied in another way. Just like the total nitrogen, these nutrients come through the fish food as fish waste. The nutrients are split up into two categories; macro- and micronutrients. Whereas the six macronutrients are way more essential for plants, micronutrients should also be taken into consideration, although they are only needed in trace amounts. Jones et al. (2013) outline that there are six macronutrients: Nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). The range of micronutrients is much bigger. Iron (Fe) is often added to aquaponics due to its general deficiency in those systems. Other important micronutrients include copper (Cu), boron (B), manganese (Mn), molybdenum (Mo) and zinc (Zn). The reader is advised to consult dedicated references or manuals on plant nutrition or hydroponics to deepen his/her knowledge on plant nutrients, for eample http://organicsoiltechnology.com/essential-elements-for-plant-growth.

Nitrogen (N) is primarily the basis for all proteins, as mentioned above. That is why nitrogen is a key element in aquaponic systems. Nitrogen needs are particularly high during plant's vegetative growth (young stages) and before fructification, but are reduced during maturity to avoid difficulties to blooming, fall of young fruits and lower quality of produce. Excess of nitrogen fertilization makes also plants more prone to pests and diseases, due to the ternderness of the vegetable tissues. Nitrogen deficiencies are very obvious; the yellowing of older leaves is a main indicator that the system lacks N. In plants, nitrogen can be reallocated within plant tissues because it is a mobile element. In case of N deficiency, N gets transferred from older leaves to new growth areas, which is the reason why N deficiency can be mainly observed in old leaves.

Phosphorous (P) is essential for the plants' DNA, phospholipid membranes, and as adenosine triphosphate (ATP). The latter can also be found in human muscles and is a component to store energy in cells. It is particularly required in young tissues. Phosphorus is essential for both photosynthesis and the formation of sugars and oils. Deficiencies can lead to poor root growth as energy cannot be transported through the plant in a proper way. Its insufficient supply causes also reddening of leaves due to antocianins or stunted growth with dark green leaves and delayed maturity. Tips of leaves might also appear burnt.

Figure 4.2 Potassium deficiency in a tomato plant

Potassium (K) is mainly involved in flower and fruit setting with the role of cell signalling via controlled iron flow through the plants' membranes. It is an enzymatic activator and supports the synthesis of proteins, carbohydrates and starch. It is also responsible for the transportation of glucose, water uptake and desease resistance. Indicators for a deficiency of potassium can be burned spots on older leaves or bad plant vigour. Also, flowers and fruits might abort or not develop properly. Being one of the limiting elements of aquaponic systems it is important to constantly supply potassium into the system, expecially if fruiting plants are grown. Figure 4.2 shows evidence of potassium deficiency in a tomato plant.

Figure 4.3 Calcium deficiency affecting tomato production

Calcium (Ca) is essential for cell walls and membranes. It has a high impact on the strength and development of stems and roots. Calcium deficiencies are very common in aquaponics. Tip burn of lettuces and blossom end rot of fruity plants can indicate that there is a deficiency of Ca in the system. Figure 4.3 shows how calcium deficiency can affect the tomato growth. The issue is that Ca only can be transported through active xylem transpiration, which occurs when the plants are transpiring. A proper ventilation to avoid a high humidity can mostly solve the problem. Calcium is one of the limiting elements in aquaponics. Calcium carbonate or calcium hydroxide supplements can be added to the system to increase the pH buffer capacity.

Magnesium (Mg) is a key element in photosynthesis and plant metabolism and is at the core of every chlorophyll molecule. Deficiencies are hardly found in aquaponic systems, but could be spotted if the area between the veins of old leaves turns yellow.

Sulphur (S) is important with respect to the production of proteins. Deficiencies are rare, but can be spotted in young leaves that turn yellow, stiff and brittle, and finally fall off.

Figure 4.4 Iron deficiency in an okra plant

Iron (Fe) is a micronutrient that is used in chloroplasts and the electron transport chain. It is critical for photosynthesis and deficiencies are often found in aquaponic systems since it is a limiting element. If there is lack of Fe, all young leaves and vegetative tips turn yellow, or eventually white with necrotic patches all over them. As iron (just like calcium) is a non-movable element, its deficiency can be easily identified when new leaves appear to be chlorotic while old leaves remain green. Iron has to be added into the system up to concentrations of 2 ppm. Iron is normally added in its chelated form, which makes this element easily available to plants. Given the susceptibility to pH it is important to keep the pH below 8 to avoid iron from precipitating and becoming insoluble. The rule of thumb is to add 5 ml of iron per 1 m^2 of plant cultivation area. Too high concentrations of iron do not harm the system but might give a reddish colour to the water. Figure 4.4 shows iron deficiency in an okra plant.

5 Production management

Aquaponics is a sustainable way to grow vegetables and other plants, as the effluent from aquaculture is used as nutrient solution for hydroponic plant production. To obtain and maintain balance in the system and secure optimal crops – the production of fish and plants, respectively has to be kept stable and the environmental parameters need be controlled as discussed in Section 4. The main production parameters are air temperature, water temperature, concentration of macro- and micronutrients, dissolved oxygen in air and water, CO_2 in air and water, pH, and light. These key parameters should be set to meet the optimal requirements of the fish and plant species being cultivated. The smaller the gap the more productive the system is. In temperate areas spring-fall crops would particularly fit cold water fish species. On the contrary warm seasons would favour warm water fish species and macrothermal plants such as tomato, cucumber and basil.

Climatic control in greenhouses can easily extend the growing season and allow farmers to produce throghought the year. However higher costs for heating and lighting need to carefully target the market prices for off-season products in order to have a chance to make profits.

Other factors of importance are to prevent insects, diseases and other source of pollution to the system. Aquaponics is less prone to diseases compared to hydroponics, where sterile conditions in substrates are maintained in lieu of heavily colonized habitats with beneficial microorganism. Nevertheless traditional aquaponics have less options than traditional organic agriculture in the use of biological compounds, which could, in some cases, be toxic to fish. In the case of pests the physical exclusion through insect-proof nets and the use of beneficial organisms (predators/parasitoids, insecticidial soaps, biological organisms) are highly effective in maintaining good crops. On the other hand, the possibility to decouple aquaponics into two quasi-indipendent systems (fish and plants) that are occasionally joined together would bring additional options in terms of organic pest and disease management.

On the nutrition point of wiew, the following of simple plant/fish ratios would ease the management of the nutrient pool, providing that limiting nutrients, such as calcium, phosphorus and iron are constantly supplied, also through buffering. According to mass balance calculations the plant biomass should be 7-10 times the fish biomass based on a feed conversion ratio (FCR) of 1. In practice 4 kg of plants to 1 kg of fish is often observed. Nevertheless a simpler rule of thumb is to use, on average, 40-50 $g/m^2/day$ of medium protein feed (32% crude protein) for leafy vegetables and 50-80 $g/m^2/day$ for fruit vegetables.

Fish management requires the maintenance of optimal growth conditions for the species being cultured. Good environment and dedicated stress management would sensitively increase the fish performance and reduce mortality. The choice of fish should take into account the local market demand and the profitability, but at the same time the capacity of the system to maintain optimal environmental conditions in order to keep costs under control. Performances of fish in aquaponics vary greatly among species, the fish growth stages, and the quality of feed used. Yet it is not uncommon to obtain FCR of 1.0-1.2 up to 1.6.

5.1 Choices of species – fish

Figure 5.1 Nile Tilapia

Most aquaponic systems have been running with Nile tilapia *(Oreochromis niloticus)* (Figure 5.1), as the main fish species. Tilapia is a tolerant warm water species and therefore a popular fish in aquaponic systems. Tilapia grows fast given the right conditions and may achieve approximately 1 kg in 8-9 months. However, the quality of water and feed will affect the growth (Martins et al., 2009). The optimum temperature is 27-28°C and the feed should contain about 30% protein. Tilapia is easy to breed, grows fast, tolerates a wide range of environmental conditions and has a nice white flesh of good quality. The market price is relatively high for good quality products. Tilapia is today the most popular farmed white fish in the world, and due to its fast growth it is often known as the *aquatic chicken*.

Over the past years tilapia has been largely used in aquaponics with interesting growth rates given optimal environmental conditions, water quality and feed. Performances on feed conversion ratio range within 1.1-1.8 (Seawright et al., 1998; Watten and Buschs, 1984; Tyson et al., 2008; Rakocy et al., 2004b), whilst recirculating tank systems show values of 1.4-1.8 (DeLong et al., 2009) and cage culture/earthen ponds can range from 0.82-0.98 (Ying and Lin, 2001) up to 1.2-1.5 (El Sayed, 2006). Likewise the fish growth rate, measured as specific growth rate (SGR: % of daily body weight increase), can be 0.91% - 5.1% in aquaponics (Seawright et al., 1998; Al-Hafedh et al., 2008), while recirculating tank systems show values of 1.4-1.8 (DeLong et al., 2009) and cage culture/earthen ponds can range from 0.82-0.98 (Ying and Lin, 2001) up to 1.2-1.5 (El Sayed, 2006).

Rainbow trout (*Onchorhynchus mykiss*) has gathered increased interest in recent years for aquaponics in the Nordic countries where it is widely grown in aquaculture, not least in Denmark being the most dominant species in Danish aquaculture (Jokumsen and Svendsen, 2010). Rainbow trout is a cold water species tolerating temperature up to 20°C and with optimum rearing temperature of 17-18°C. This complies well with the optimal temperature in salad production of 15-19°C. A temperature control would be needed to secure water temperatures below 20°C at all times, as higher temperatures will stress the fish and even kill it. On average it takes 7-8 months to grow rainbow trout from 20 g to 300 g (portion size) in RAS in Denmark (Dalsgaard et al., 2012) and the protein content needed in feed for good growth is 45-50% and higher for juveniles. The researchers at Nibio in Grimstad, Norway have carried out studies in aquaponics based on rainbow trout and salad production with good results providing excellent quality and good growth rates.

Developments in RAS have resulted in effective model trout farms with fish density of approximately 50 kg/m^3, a water of maximum 0.15 l/sec/ton feed/year or 3,600 l per kg produced fish with a FCR close to 1.0. This is 15-25 times lower water consumption than in traditional flow-through fish farms (Jokumsen and Svendsen, 2010). Today the waste water is drained to so-called plant lagoons for cleaning. The plants themselves are not used as commercial products, and thus it is seen as a natural step further to add plant production systems to the RAS systems and turning these into aquaponics. Further information about farming rainbow trout in RAS can be found in dedicated literature (Jokumsen and Svendsen, 2010; Dalsgaard et al., 2012).

Table 5.1. Water quality parameters observed under general conditions in operating, commercial or pilot scale RAS (Daalsgaard et al., 2012)

Parameter	Temp (°C)	DO (mg/L)	CO_2 (mg/L)	pH	Salinity (ppt)	TAN (mg/L)	NO_2-N (mg/L)	NO_3-N (mg/L)	Density (kg/m^3)
Arctic charr	5-12	9-11	≤22	6.5-8.5	<24-26	≤1.0	<0.50	<10	85-130
European eel	23-28	6-8	10-20	5.0-7.5	0-5	0.0-5.0	0-1.50	50-100	50-120
Pike perch	22-25	6-8	10-20	6.5-7.5	0	0-10.0	0-1.50	≤56	15-60
Rainbow trout	2-21	6-8	≤15	6.5-8.0	0-30	<7.5	<1.00	<200	50-80
Sturgeon	18-25	8	n.a.	7.0-8.0	0	<3.0	<0.50	<25	80-100
Tilapia	20-30	4-6	≤30-50	6.5-8.5	≤10-15	<3.0	0.05-1.00	100-200	85-120

Aquaponics can be run with a wide range of fish but in all cases the environmental criteria has to be met for the chosen species. Table 5.1 compares water quality parameters for different species in RAS. On a qualitative point of view RAS and aquaponics proved that the fish containment helps to prevent any risks of parasites or chemical pollution from external water sources. On the other hand the rearing of fish in closed systems has proven no risks of heavy metal build-ups in fish meat compared to the levels found in animals reared with traditional systems (Martins et al., 2010).

Other fish also have shown interesting perfomances in aquaponics if compared against RAS. In the case of young African catfish SGR from aquaponics (1.36% - 2.13%) (Endut et al., 2010; Pantanella et al., 2011a) is similar to recirculating systems (1.24% – 1.94%) (Pantazis and Neofitou, 2002; Ahmad, 2008). Likewise FCR in aquaponics (0.97 – 1.39) (Endut et al., 2010; Pantanella et al., 2011a) is similar to recirculating systems (0.94 – 1.29) (Degani et al., 1988). In temperate areas some species may have interesting market opportunities that specifically meet customers demand. Aquaponics has proved to have good performances for sturgeon grown at 19.5°C (FCR 1.01-1.25, SGR 1.38-1.66) (Dediu et al., 2012); Murray cod (Maccullochella peelii peelii) reared at 22°C (FCR 0.8-1.1; SGR 0.9-1.1) (Lennard and Leonard, 2006); and Largemouth bass reared at 26°C (FCR 1.5; SGR 0.7) (Pantanella, unpublished data).

5.2 Choices of species – plants

Plants in an aquaponic system need to have good environmental conditions for good and healthy growth. They require optimum conditions in comparison to, light, oxygen, carbon dioxide, pH, temperature and nutrients, which eventually secure fast and healthy growth against pests and diseases. Several crops have been produced in aquaponic systems and many of them have performed very well. The soilless plant production starts by seed, cuttings or by transplants.

Figure 5.2 Lettuce (*Lactuca sativa*) produced at Nibio in Grimstad

Figure 5.3 Okra and pak-choi produced by Svinna in Reykjavik

Leafy vegetables fit well in aquaponics and most types grow well in aquaponic systems. At Nibio in Norway the growing of lettuce (*Lactuca sativa*) (Figure 5.2) has been successful in the pilot aquaponic systems. It has shown high growth speed and it has been well received by customers. The price for good quality and single packed heads is relatively high. Good varieties are *green oak*, *crispy*, *green cos* and *butter-head*. Svinna in Iceland has grown the Asian plants pak-choi, malabar spinach and okra (Figure 5.3) with good results in aquaponics with great consumer acceptance.

The main plant species grown so far in aquaponic systems is lettuce, which has been grown under different densities (16 to 44 plants/m^2) and crop lengths (21-28 days), mainly on floating raft systems, and provided variable yields ranging 1.4-6.5 kg/m^2 per crop (Rakocy et al., 1997; Seawright et al., 1998; Lennard and Leonard, 2006; Dediu et al., 2012). Basil is also a widely tested crop with densities of 8-36 plants/m^2 that brought to yields of 1.4 to 4.4 for crop cycles of 28 days (Rakocy et al., 2004a; Pantanella et al., 2011b). Warm temperature crops also proved to be very productive, as in the case of water spinach, yielding 33-37 kg/m^2 in 28-days crop at a density of 100 plants/m^2 (Endut et al., 2010), while okra could yield 2.5 – 2.8 kg/m^2 in less than three months at densities of 2.7 and 4, respectively (Rakocy et al., 2004b). Speciality and culinary herbs such as salicornia and salsola could provide yields up to 7 kg in 110 days and 5 kg in 28 days, respectively (Pantanella et al., 2011c; Pantanella and Rakocy, 2012). Thus, the annual plant production in aquaponics has shown to be varied between species. In trials run by Savidov in Alberta Canada (Savidov, 2010), water spinach and swiss chard made around 50-60 kg per square meter per year while amaranth, lettuce, basil, choi, parsley and spinach made around 20-30 kg (Figure 5.4).

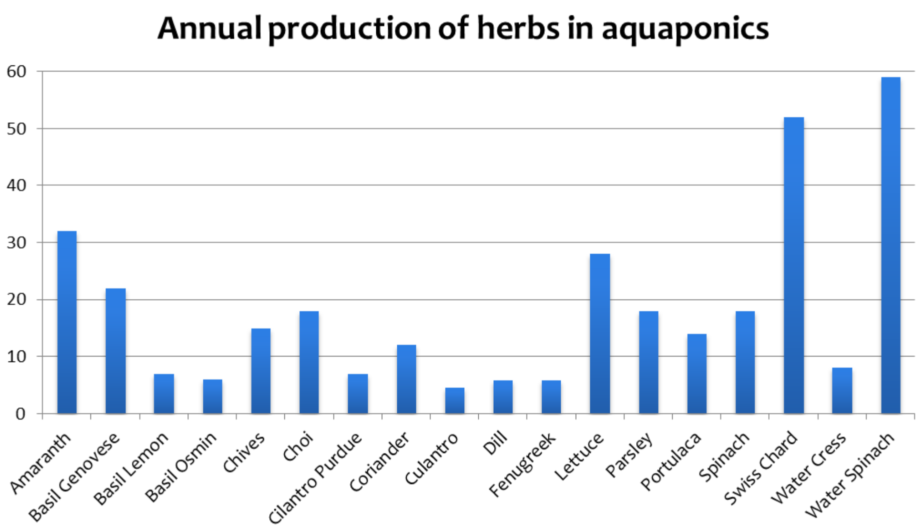


Figure 5.4 Annual production kg per square meter of leafy greens in aquaponics (Savidov, 2010)

Another interesting result from aquaponics testing is the difference concerning yield between aquaponics and hydroponics. In mature systems aquaponics outperforms hydroponics for tomato (31-59 kg/m^2 vs 41-45 kg/m^2) and cucumber (42-80 kg/m^2 vs 50 kg/m^2) with balanced N:K ratios (Savidov, 2005). Other fruity plants can still perform well against hydroponics, such as the case of aubergine (7.7 kg/m^2 vs 8.0 kg/m^2 in 105 days) and tomato (23.7 kg/m^2 vs 26.3 kg/m^2, in 43-67 days), but cucumber seems to show reduced performances (3.3 kg/m^2 vs 5.2 kg/m^2, in 42 days) (Graber and Junge, 2009). Nevertheless optimal N:K ratios provide similar cucumber yields to hydroponics (7.6 kg/m^2 vs 7.5 kg/m^2, in 48 days) and quality of fruits (sweetness, vitamin C, dry matter) (Pantanella, unpublished data). For leaf vegetables there are no differences between aquaponics and hydroponics for both lettuce and basil productivity and leaf quality, both for chlorofill, leaf area, leaf to stem ratio and nitrate content of vegetable tissues (Pantanella et al., 2011a, 2011b, 2012), also plant growth in aquaponics nutrient water was higher. This study indicates that there is a factor stimulating nutrient uptake and assimilation by plants grown in aquaponics solutions, where nutrient and many organic compounds are derived from fish feed (Savidov, 2010). Tomatoes, as well as most vegetables may also have assimilated nitrogen in amino acid forms. Ghosh and Burris (1950) found that tomatoes use alanine, glutamic acid, histidine and leucine as effectively as inorganic nitrogen sources.

5.3 Quality and production of edible plants

So far plants growing in aquaponic systems tend not to get diseases. The plant disease referred to as “pythium” or “root rot” (Figure 5.5), estimated to kill 30% of hydroponically grown plants, is virtually unknown in aquaponics. The conclusion of this is the fact that while hydroponic system is a largely sterile system, aquaponic systems are full of beneficial bacteria and microbes that help plants to combat disease (Bernstein, 2011). Nevertheless, integrated disease management must always take into account the environmental susceptibility of the plant and the pathogen and modulate the physico/chemical parameters to conditions that are more favourable to the plants. Control of water temperature, ventilation, dew point, pH, optimal nutrient balances are all abiotic parameters that help to prevent or control diseases. In the case of phytium, the root rot disease, the pathogen spreads with favourable temperatures above 27-28°C, thus control of water, together with inoculum of beneficial organisms are a must, if the shift to alternative crops is not considered.

Figure 5.5 Root rot from phytium (left) vs healthy roots (right)

Nutrition for living organisms plays a fundamental role, as certain nutrients in excess or in limiting concentrations favour the diffusion of pathogens. Nitrogen is important for the vegetative growth of plants, but it makes plants tissues more succulent and thus prone to attack of the pathogens if not correctly balanced with other nutrients.

During the production it is important to observe plant health and the colour of leaf. Also the leaf shape can tell if the plant is doing well. Wilting and signs of stress can be useful information for the producer to investigate plant health issues (root, collar, vascular problems) as well as for nutrient unbalances.

If the crop is beginning to look unhealthy after the first few months it is a good idea to check the nutrient profile of the water to find potential imbalances. These imbalances can be caused by out-of-range pH. It is important to maintain pH between 6.0 and 7.0 for optimal nutrient uptake by the plants and good working conditions by nitrifying bacteria. Also, it is imporant not to choose plants that prefer an acidic or basic root environment, besides any other plant can be grown in this sustainable system (Rakocy, 2011).

Plants need to have optimum growth rate to be a great partner in clearing waste water from fish – and making aquaponics to a commercial economical winner. An important issue is also the microbiological quality of aquaponics productions, expecially for leaf vegetables. Besides the compliance to hygiene standards by operators and plant management to prevent contamination by coliforms it may be worth considering the use of sterilization to bring aquaponics within the water safety standards for irrigation water. Past researches have already proven that aquaponics are free from *Escherichia coli*, but a full control of coliforms withouth harming both plants and fish should be possible (Pantanella et al. 2015).

5.4 Societal factors

It is important that cities reclaim foods that have characteristic of their community strengthening the communal bonds between the residents. In addition, these foods can generate jobs and revenue for the community (Yang, 2012).

Likewise, there has been a fast growing interest in urban farming in both developing as well as developed countries since the world food crisis of 2007. The vulnerability and dependency of food for the urban community already reaching 60% of the world population, and its relience on a very concentrated food system made it clear for a growing number city councils as well as a varied range of non-governmental organizations (NGO‘s) that change in the foodsystem from ‚farm to fork‘ had to change[16].

Aquaponics is becoming very popular among these various urban farm initiatives around the world. This is especially true for community building in areas of unemployment, food security issues and social problems; other factors include educational awareness through giving a simple overview of the complexity of nature and recycling.

Aquaponics related to urban farming are still based on small production units due to first and foremost the requirement of a large plant area when more simple systems are in use. The potential introduction of more modern biofilters or decoupled production systems opens up for larger scale industrial based aquaponics. However, the closer you move an urban farm away from the peri-urban zone to the inner city center the more space becomes a physical issue as well as a constraint for establishing a financially viable food business. The latter is true with regards to space becoming a scarce resource in competition with other economic sectors. Therefore the many “empty” or “free” roof spaces of a city has gained increased focus for potential areas of food production, but requires often an expensive change in the present building construction to carry an urban farm.

5.5 Risk analysis

A risk analysis (Table 5.2) shows the main risks in an integrated aquaponics production system and how these can be minimized. The results show that monitoring and controlling the crucial environmental parameters is essential to maintain a healthy and stable system. The risk contingency plan includes the prevention of pollution leading to fish and plant diseases, maintaining a secure system control for a balanced environment, securing good quality of products and understanding market needs.

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[16] http://www.urbanagricultureeurope.la.rwth-aachen.de/

Table 5.2. Risk analysis for aquaponics

Risk	Probability	Severeness	Contingency plan
Fish disease	Low	Medium	Strict management procedures, dividing production systems into units, controlling and keeping a healthy environment and cleaning tanks between stocking
Plant pest	Low	Medium	Strict management procedures, organic defences, integrated pest management
Failure of temperature control	Low	High	Online monitoring and automatic control with alarm system
Oxygen level too low	Low	High	Monitoring and control, improvement of aeration, reduction of stock
Failure of pH control	Low	High	Monitoring and control
Sodium levels too high	Low	Medium	Monitoring and control, shift to different feed sources
Failure of EC control	Low	Medium	Monitoring and control
Contamination of water	Low	Medium	Monitoring and control, safety procedures
Marketing failure	Low	High	Keeping good quality, fulfil official requirements, and inform consumers about the production processes
Extreme weather conditions, earthquakes, volcanic eruption	Very low	High	Initiate emergency plan minimizing losses

6 Market and certifications

Aquaculture has quickly grown from a minor, niche industry into an industrialized and modern one, and sustainability is at the center of many innovations on how to make this arena a long-term and thriving success. Output for food production from aquaculture has now surpassed that of wild capture fisheries, but also with having growing negative environmental and social impacts.

In the past decade, internationally recognized standards regulating different facets of the farming practice, from food safety to social accountability to environmental sustainability, have gained a foothold in the aquaculture industry. The original emergence of eco-certifications occurred as government agencies stepped away from trying to regulate what constitutes sustainability. Although recently governments have started to re-engage and increase participation in defining ecological limits, certifications provide a voluntary regulatory interface, usually with a consumer-facing label.

No current certification scheme covers all of the issues essential to ensure that products come from sustainable and fair aquaculture operations. Each certification represents its own range of criteria and set targets. Some are species specific, while others cover aquaculture production in general. Third-party standards dominate the certification world, but there are also a few retailer-based standards or sourcing criteria.

It is then the responsibility of retailers to ensure that the products they buy come from operations adhering to the conditions described above. Retailers must, until a reliable certification system is in place, communicate to their customers the sustainability of their products.

Product standards and eco-certifications act as shorthand for buyers at the marketplace, a seal of approval to guide consumer decisions. Many producers are learning that certifications are becoming a necessity to stay competitive at the sales counter.

There are a number of incentives for producers to become certified. The certification label provides an easy recognizable signal to consumers that a product meets a certain level of performance, as defined by the standard. This can improve public perception of farmed seafood in areas where consumers are more wary or where there have been concerns regarding ecological impact. Although each certification sets its own targets for sustainability, the process of certification provides verification for producers since third party audits are required.

In addition to building legitimacy in the public eye, certification can provide producers with access to certain retailers, and/or retailers and buyers that require compliance with a minimum performance.

6.1 Organic certification

Organic certification is of close interest to an aquaponics producer since the whole system is based on a holistic thinking in terms of recycling, lowering the resource intake and securing zero pollution. However, it is only possible to have a full aquaponics production system certified organic if the plants are grown in soil, and the fish produced are sold as fingerlings for further growth in open organic based pond systems. There is a need for a review of these standards.

The regulatory framework for organic fish and horticultural production in the EU is regulated by the Council Regulation (EC) No. 834/2007 whereas more detailed rules are regulated by (EC) No. 889/2008, (EC) no. 710/2009 and (EC) 834/2007.

6.1.1 Horticultural produce

The present regulatory regime does not have any standards or regulations for certifying organic aquaponics. The organic regulation only deals with separate aquaculture and horticulture production. Each separate regulation hinders in various degrees the prospects of taking a holistic approach and work towards an organic certification for aquaponics.

For organic horticultural production current regulation 889/2008/EC, implementing regulation 834/2007/EC, contains only one element specific to greenhouse production:

art. 4 which bans hydroponic production and allows organic cultivation only in soil.

Since most aquaponics production systems are based on a soilless hydroponic technology, the plants produced under such a system cannot be certified as organic. This opens the only option to adopt culturing practices on soil through decoupled aquaponics/RAS waste water.

6.1.2 Aquacultural produce

For organic aquaculture the production is regulated by (EC) 889/2008 and (EC) 710/2009. In parr. 11. (EC) 710/2009 recirculating systems are clearly prohibited except for the specific production in hatcheries and nurseries:

> *Recent technical development has led to increasing use of closed recirculation systems for aquaculture production, such systems depend on external input and high energy but permit reduction of waste discharges and prevention of escapes. Due to the principle that organic production should be as close as possible to nature the use of such systems should not be allowed for organic production until further knowledge is available. Exceptional use should be possible only for the specific production situation of hatcheries and nurseries.*

Since recirculating technology is the core of the aquaponics production system it is at present not possible get an organic certification on aquaponics at all, and hence have both fish and horticultural products certified as organic.

If the plants are grown in soil, like the IGFF system, it is possible to have the horticultural produce certified as organic – but not the fish. As a contradiction to this - within the organic regulation itself the horticultural produce is allowed to be fed by a certain percentage of conventional fish feed, similarly to an organic plant production receiving conventional manure.

The question remains whether it is possible to optimize the total finance in an aquaponics production if the plant production is to be fed by a more expensive organic fish feed, yet the fish are not allowed to be sold as organic and hence obtain a higher premium.

6.1.3 Future of organic aquaponics

The crux for aquaponics producers to get an organic certification lies to get an acceptance in the future of the recirculating technology.

Short-term strategies in this regard could be to:

1) View aquaponics as a farm based on a necessary harmony and biomass ratio between husbandry (the fish), and a soil-based horticultural production as the field turning waste into valuable resources and providing a food production with no discharges to the environment.

2) Work towards a specific regulation on aquaponics. This would imply allowing recirculating technology where a potential misuse of intensification in the fish production is already guided by the organic regulation on the number of fish allowed per m^3 water, as well as a natural constraint in the required horticultural production to use the fish nutrients.

Paragraph 24 in the (EC) regulation 710/2009 opens up for an interpretation that such steps could be allowed:

> *Organic aquaculture is a relatively new field of organic production compared to organic agriculture, where long experience exists at the farm level. Given consumers' growing interest in organic aquaculture products further growth in the conversion of aquaculture units to organic production is likely. This will soon lead to increased experience and technical knowledge. Moreover, planned research is expected to result in new knowledge in particular on containment systems, the need of non-organic feed ingredients, or stocking densities for certain species. New knowledge and technical development, which would lead to an improvement in organic aquaculture, should be reflected in the*

> *production rules. Therefore provision should be made to review the present legislation with a view to modifying it where appropriate.*

Especially the last lines in Parr. 24 implies that national initiatives could be taken with the aim of improving the common EU regulation on organic aquaculture. This would require a more dedicated willingness in the organic movement to commence a process in this direction.

7 Added value

Several added value products and services can be combined to the aquaponics development to establish a viable business. Some of the implemented aquaponics companies already have started aquaponics education based on their know-how, skills and pilot units. The most famous aquaponics education is probably the aquaponics training programme at the University of Virgin Islands[17]. However, many other entrepreneurs have taken on the task to educate people in aquaponics.

Figure 7.1 Red claw crayfish (*Cherax quadricarinatus*) from Svinna´s pilot unit

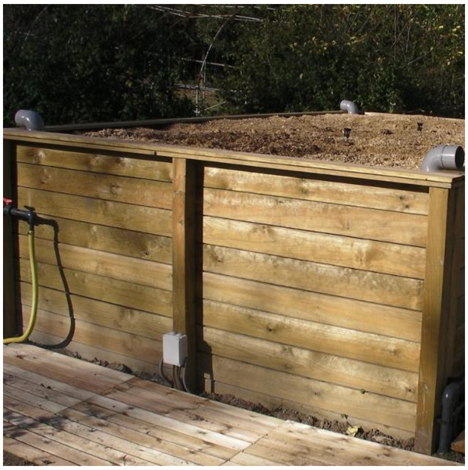

Figure 7.2 Worm cultivation at Breen

Other ideas are byproducts such as using the sludge for crayfish production (Figure 7.1), worms (Figure 7.2), insects, or fertilizer production through aerobic or anaerobic digestion. Also the aquaponic systems provide a tourism attraction in education related experience. A visiting centre can be linked to the production unit, with direct sale of products and even a restaurant as is the case in Tropenhaus in Switzerland[18]. Eco-tourism is growing constantly over the last couple of years. Linking aquaponics to tourism could be promising, especially as horticulture/hydroponics visitor centers such as Fridheimar in Iceland (www.fridheimar.is) are booming. More central and especially urban aquaponics installations combined with restaurant units and education centers could raise awareness in that field and be an independent economic business based on: tourism, education, food production, and gastronomy. This is an excellent example of business diversification that could be a blueprint for locations all over the world.

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[17] http://www.uvi.edu/research/agricultural-experiment-station/aquaculture-home/aquaponics-workshop/default.aspx
[18] www.tropenhaus.ch

Technology and equipment providers have been showing increased interest for aquaponics in recent years. In general aquaponics have been moving from simple and inexpensive boxes and home made units to industrial equipment used in conventional aquaculture and horticulture as the systems become larger aiming for commercial scale production. There is room for novel ideas that link the two different production methods into one and this also includes monitoring and control systems.

8 Conclusion and future perspectives

The energy cost is increasing and the world is not only going through "peak oil" but also "peak phosphorous", making energy and fertilizer constraints on food production (Ragnarsdottir et al., 2011; Sverdrup and Ragnarsdottir, 2011). Higher energy prices directly affect food prices. At the same time the use of waste heat and geothermal heat is suboptimized. Traditional aquaculture and horticulture produce waste impacting the environment, waste that contains valuable nutrients that could be circulated into other food products. Moreover, water scarcity is becoming a problem in many countries due to climate change and changing precipitation patterns. This is fast becoming a global problem and is inherently linked to resource management, population growth and food security. Thus, the world needs new technologies for optimum use of water, nutrients and direct use of waste heat and geothermal energy for food production.

In aquaponics there is no waste, as all materials are valuable inputs in the production cycle. Thus, aquaponics aims to mimic a natural system with optimal use of all nutrients, water and energy. It uses no pesticides, herbicides, hormones or medicine. Thus, it is an industrial chemical free production system. However, it may still be difficult to have the production certified as the standards for aquaponics are under development and traditionally organic certification of plants have required soil in the system and RAS is not allowed in organic aquaculture.

At present, the interest in aquaponics is increasing globally. In Europe several strong collaboration networks have been established e.g. the COST FA1305 Aquaponics hub with 23 participating countries. Several ongoing projects in semi-commercial scale aquaponics and research units are delivering results to support successfully-upscaled aquaponic systems capable of contributing to a new integrated and sustainable food production methodology.

Until now, aquaponic systems are coupled; which means RAS and hydroponics form one loop or at least have common sump and filtration units. Decoupled aquaponics would mean that those loops are separated enabling optimum environmental conditions in both the RAS and hydroponics part eliminating trade-offs. Emphasis would still be on zero-waste solutions and making maximum value out of all resources. The first steps towards such systems have been taken and it will be interesting to follow the future developments.

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