Chapter 7
Aquaponics Production, Practices and Opportunities

Edoardo Pantanella

Abstract Aquaponics is a plant production system that integrates soilless cultivation and recirculating aquaculture. Aquaponics is an environmentally-friendly system that makes full reuse of wastes that are used as fertilizers for plants. At the same time it is more productive than soil-based agriculture and has consistent water savings, which makes it the ideal technology to produce food in resource-limited and climate-change affected areas. The chapter seeks to provide an understanding of aquaponics by giving an overview of the state of the art of past and current research and by outlining advantages and disadvantages of aquaponics against traditional agriculture (soil, soilless) and aquaculture. A comprehensive description of the aquaponic components is given together with a summary of the different systems in use, providing keys for understanding their characteristics and suitability in different climatic and operating conditions. Beside the production of quality crops for both market and backyard consumption, aquaponics could be a tool to address food insecurity in developing countries. Furthermore, new opportunities for aquaponics are also seen in the use of saline waters to provide tool for bioremediation of brackish-water and marine aquaculture, but management systems need to be adapted to the range of salt-tolerant plants and seaweeds available for either food, feed or fuel, as well as the market demand.

Keywords Integrated aquaculture · Soilless cultivation · Hydroponics
Zero-waste · Sustainable farming

E. Pantanella (✉)
CIHEAM IAM Bari, Valenzano, BA, Italy
e-mail: edpantanella@gmail.com; pantanella@iamb.it

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7.1 Overview

There is a significance concern about how future generations will produce more in a sustainable way. Intensive food production forces agriculture to overexploit natural resources: the conversion of natural lands/forests into arable lands, the pollution from the massive use of fertilizers and chemicals, the reduction of soil fertility and carbon stocks are indeed some of the main raising issues on farming sustainability (Tillman et al. 2002). In the last twenty years the nitrogen content in the oceans has increased by twenty times due to the indiscriminate use of fertilization (Downing et al. 1999) causing severe eutrophication to water bodies. Therefore, the closing of the loop between inputs and wastes, such as the re-reuse of crops and animals by-products, is one of the few possibilities to improve the water and nutrient efficiency and to reclaim organic wastes back to useful productions. The pace in achieving higher crop productivity, as it was during the Green Revolution in the sixties, raises questions whether higher outputs from agriculture are still possible by technical or scientific breakthroughs (Brown and Kane 1994; Waggoner 1994). There are robust evidences that natural resources, such as water and fossil energy, are over exploited (UN-Water 2012) and cannot easily guarantee further agriculture expansion. The conversion of wild lands to agriculture, such are forests, not necessarily has brought long lasting advantages for food production due to the low fertility or the fast degradation of the soil, which eventually has caused irreversible losses of land. At the same time the excessive intensification of agriculture in fertile productive areas if from one side has disrupted natural ecosystems through the massive use of fertilizers and pesticides, from the other side has progressively reduced the fertility and productivity. Therefore the increased pressure on production makes the exploitation of natural resources inevitable unless new strategies and production techniques are adopted to make farming systems more self-sufficient and resilient.

In the case of horticulture the adoption of soilless agriculture, more commonly known as hydroponics, shows undoubting advantages for its higher nutrient and water use efficiency compared to soil based agriculture (Resh 2004; Leoni 2003). Hydroponics shows in fact yields that are 2–3 fold higher and water consumptions patterns that can be up to ten time lower than traditional farming. This is due to the improved water distribution and the better growing conditions of plants that receive punctual fertilization of nutrients with no competition from weeds as well as limited risks of pests and soil-borne pathogens.

Likewise, the farming of animals with the lowest footprint and the highest feed conversion efficiency, would eventually reduce the impact on water and land and increase the overall food output (Verdegem et al. 2006). In the case of fish the adoption of recirculating aquaculture systems (RAS), in which the fish rearing water is almost completely recycled after a filtration stage, can reduce the water footprint of traditional aquaculture by hundreds of times and avoid any discharge of organic wastes (fish excrements, uneaten feed) into the environment.

Aquaponics combines the benefits from both soilless culture and RAS. The build-up of nutrients in a closed aquaculture system can in fact reach concentrations that are ideal for the commercial production of plants. At the same time plants take up nutrients and reclaim water back to fish by also adding a profit from the costs for water treatment normally occurring in RAS. Aquaponics allows intensive and high-quality production of vegetables without any impact on the environment for either pollution from chemical fertilizers (agriculture) or animal wastes (aquaculture).

The present chapter aims at exploring the potentials of the integration of aquaculture with soilless culture for the sustainable development of agriculture in rural areas and wherever traditional agriculture could not be efficiently developed due to disturbed soil or adverse environmental conditions. Aquaponics is analysed in its components and compared against aquaculture, hydroponics and traditional agriculture practices, with the objective to unveil its advantages and disadvantages in the context of sustainable food production and food security.

7.1.1 What Is Hydroponics

Hydroponics is a combined word that joins two Greek terms: water (hydro) and work (ponos). Plants grow by means of a nutritive solution in which adequate quantities of macro and micronutrients are dissolved to support their growth. Hydroponics is also called *soilless culture*, as plants do not grow on soil but rather on inorganic substrates (sand, gravel, perlite, rockwool slabs) (Fig. 7.1), organic substrates (peat, sawdust, rice husk) or even with bare roots within an aqueous media (floating system) (Fig. 7.2). Substrates in soilless culture provide only mechanical support to the plants.

Hydroponics moved its first steps in commercial production in the first half of the 20th century following the intensification of agriculture and the need to overcome the problems of soil-borne diseases caused by the continuous monoculture practices in the greenhouses (Leoni 2003). Further expansion occurred from the fifties, when the adoption of plastic lowered the production costs and made the investment on greenhouses and climate control affordable by many (Resh 2004). The initial use of bulk substrates was successively substituted by the nutrient film technique (NFT) and the adoption of rockwool in the seventies, which opened up new horizons in commercial-scale horticulture.

Nevertheless hydroponics has a long history that witnesses the constant research of farmers for more productive and cost-effective solutions under different designs and plant nutrient sources, even with low-tech approaches.

In the Middle East the hanging gardens of Babylon, built more than 25 centuries ago, were the first example of soilless roof-top agriculture that used sludge and ash as plant nutrients (Leoni 2003).

In Mexico organic matter was the growing media and fertilizer used for the chinampas, a type of integrated aquaculture-agriculture system in shape of terrains surrounded by canals. The production of food with this technique was one of the most intensive agricultural system in the pre-Colombian era (Sutton and Anderson

Fig. 7.1 Hydroponic tomato on Rockwool media

Fig. 7.2 Small floating system with a plant bed and nutrient tank

2004) to the extent that chinampas could support the food needs of 10–18 people per hectare (Adams 2005), which is far above the current productivity of modern soil-based agriculture. The common factor that favoured the diffusion of all these agricultural systems was the lack of cultivable land and the need to increase the acreage for crops, a common problem still existing in many flooded areas of developing countries.

In S.E. Asia floating agriculture is still in use as a low-tech type of hydroponic. Floating rafts made of aquatic macrophites (i.e. water hyacinths) provide both support and nutrients to plants through the release of minerals released from the decaying organic matter. In the Inle Lake in Myanmar such type of system is still the backbone of local horticultural productions that supply vegetables to the domestic markets.

Nevertheless the solutions provided by floating agriculture can well integrate traditional aquaculture systems, such as ponds, in which quality vegetables can grow on water with yields that are similar or higher than soil crops (Pantanella et al. 2011d). At the same time floating rafts made with decaying organic matter can release nutrients in ponds to promote microalgae blooms that constitute the food of planktonic fishes. On the other hand floating pots filled with inert media that are suspended on pond water can provide tools for bioremediation for intensive farming by simply stripping nutrients from water.

7.1.1.1 Advantages of Hydroponics Against Soil Production

Soilless cultivation addresses many issues of traditional farming. The presence of an inert media in lieu of soil allows plants to grow with very limited incidence of soil-borne pathogens and pests. At the same time the hydroponics' real-time delivery of nutrients, which are monitored and distributed according to the growth stage of the plants, maximizes the productivity and quality traits of the produce. The lack of soil also avoids any need for weed control, which directly helps the crops to grow without the competition for nutrients and space by invasive plants. The delivery of water and nutrients is also engineered in such a way to avoid any leakage or spill outside of the system, thus minimizing any pollution risks. Such controlled management let hydroponics be up to ten times more efficient in its water use efficiency than traditional agriculture.

Hydroponics is at least 20–25% more productive than soil-based intensive greenhouse farming, which makes massive use of fertilizers and soil sterilization (Resh 2004). On the other hand for outdoor crops hydroponics shows 4–10 times higher yields than soil (Table 7.1).

Soilless cultivation is ubiquitous, as it allows to produce food even in places where traditional agriculture cannot be developed due to unsuitable soil or water scarcity: deserts, salinated or unproductive lands, roof tops in urban areas, contaminated land under reclamation.

The advantages of hydroponics against conventional agriculture can be summarized in the improved adaptability to farm in unfavourable areas, in the better efficiency of inputs' uses, in the higher yields and qualitative traits, in the reduced use of chemicals to overcome plants' soil-borne diseases (Jensen 1981, 1997; Tesi, 2002; Resh 2004) (Table 7.2).

Table 7.1 Comparative yields per hectare in soil and soilless culture (Resh 2004—modified)

Crop	Soil ton ha^{-1}	Soilless ton ha^{-1}
Beans	12.5	52.5
Beets	10.0	30.0
Cabbage	14.7	20.3
Cucumber	7.9	31.6
Lettuce	10.2	23.7
Peas	2.5	22.5
Potatoes	20.0	175.0
Tomatoes	12.5–25	150–750
Wheat	0.7	4.6

Table 7.2 Soil versus soilless production

	Soil	Soilless
Farming in new areas	Not always possible. Depends on the type of soil, fertility, salinity	Agriculture possible in any condition
Cultivation	Constant preparation of soil, need of machines, fuel intensive	No needed, substrates preparation or positioning on troughs/ground
Intensification of production	Limited. Monoculture brings “soil tiredness” and already decreases yields after two successive crops Soil tiredness requires crop rotation, fallow or soil sterilization, which is time consuming and interrupts crop cycles for 2–3 weeks	Monoculture is possible with no decadence of performances Substrates could be sterilized with simple means and no crop interruptions Inert media or water do not face risk of any fertility losses due to their characteristics
Plant nutrition	Variable delivery. The release depends on soil characteristics. Some deficiencies are possible. The precise delivery of nutrients according to the plant growth stage is not possible	Real time distribution of nutrients and pH according to the growth stage of the plants. Real-time control of the levels of nutrients required by plants
Nutrient use efficiency	Fertilizers broadcasted broadly, High dispersal through leaching and runoff in outdoor conditions	Minimal amount required due to microirrigation and containment of media. Water and nutrients monitoring avoid the loss of nutrients
Water use efficiency	Efficiency affected by soil texture and irrigation system	Optimal delivery trough microirrigation supported by sensors
Weed control	Need continuous control	No need of any control
Diseases and pests	Affected by soil-borne diseases and pests. Needs sterilization, crop rotation	Not affected because of no use of soil
Quality	Product characteristics depends on of the type of soil and management	Standardized production with full control of nutrients. Optimized growth

(continued)

Table 7.2 (continued)

	Soil	Soilless
Production costs	Normal, but use of machinery necessary for soil cultivation and higher use of inputs (water). Higher costs if greenhouses/nethouses are used	Higher costs due to more expensive setting in greenhouses/nethouses and the presence of a monitoring system,
Farm management	Standard level	Expert level. Needs higher knowledge for the higher technology used

7.1.1.2 Hydroponic Systems in Use

Hydroponic systems are classified into two main categories depending on whether plants grow with their bare roots in an aqueous media or if they benefit from the mechanical support given by substrates (Resh 2004). The first type, also called water culture, is the most used especially for leafy vegetables. Three main designs are used: nutrient film technique (NFT), deep water culture or floating system (DWC) and aeroponics.

Nutrient Film Technique (NFT) consists of flat-bottomed plastic pipes with holes on their top in which plants are positioned (Figs. 7.19 and 7.20). The plants' roots develop inside the pipes. A thin layer of nutritive solution wets the bottom of the pipes at a very low water flow (1–2 L min^{-1}) supplying plants with nutrients and water. In general the water flow can be continuous or intermittent, in the latter case roots take some additional oxygen from the air. This type of system is mainly closed, with water continuously recirculating between the troughs and the tank containing the nutritive solution, where water get oxygenated.

Floating system/deep water culture (DWC) consists of tanks of variable depth (from 7 to 30 cm) on which plants grow supported by floating polystyrene rafts (Figs. 7.15 and 7.16). Plants have bare roots into the nutritive solution, which is kept aerated by air stones. The volume of water allows for multiple production cycles, with nutrients being re-integrated from tanks containing concentrated stock solutions. The system is quite resilient against black outs, as oxygenated water is always in contact with the roots. DWC is largely used for leafy greens, culinary herbs and a variety of fruity plants (Leoni 2003).

Aeroponics has plants roots suspended in the air continuously wetted by nozzles spraying the nutritive solution. Plants are positioned on oblique trays to optimize the space into greenhouses and to create a volume for the spraying systems. Like the NFT the nutritive solution is continuously collected into a sump and minerals are reintegrated from tanks containing stock solution. Aeroponics needs the uniform distribution of the nutritive solution to the roots to guarantee a uniform growth, and a tailored management of the spraying cycles, which vary according to the type plants and their growth stage (Leoni 2003). Aeroponics takes advantage of the great root oxygenation, but it is prone to wilt in case of any disruption in the water distribution system.

Substrate culture has plants growing in pots, beds or bags filled with a growing media. There is a wide range of organic or inorganic media available, each with different characteristics, prices and availability: peat moss, sawdust, coconut, rice husk, rock wool, sand, gravel, perlite, clay balls, polyurethane, and polystyrene. The media is always kept separated from the ground underneath to prevent any risk of contamination with the soil. The nutritive solution can be delivered through micro-irrigators, sub-irrigation or ebb & flow (cyclic flood and drain of the media with the nutritive solution). The media systems can be either open (flow-through), with the nutritive solution used only once, or closed with a continuous recycling of the water (Tesi 2002; Resh 2004).

7.1.2 What Is Aquaponics

Aquaponics is an integrated system that combines hydroponics and recirculating aquaculture. Plants grow using the nutrients dissolved in the aquaculture effluents and provide tools for bioremediation by reclaiming the wastewater back to fish.

There have been many types of integrations between aquaculture and agriculture in the past, with fish water mainly delivered to the plants in open systems. Examples can be seen in the irrigation of crops with pond water or in ditch-dyke systems, where narrow strips of land are surrounded by a network of small water canals stocked with fish. The uptake of water for irrigation from the ponds, which are then refilled with new aqueous sources, is undoubtedly a good practice to maintain good water quality for healthy fish growth and to reduce the impact of aquaculture pollution (Barnabé 1990; Diana et al. 1997).

The feeding of fish in fact increases the levels of excreted ammonia into the water, whose build up is toxic for the aquatic animals. Therefore, the progressive intensification of aquaculture production, with higher fish densities, needs increased water exchange to avoid toxicity and deaths (Barnabé 1990). Although these integrated systems cover the water needs of the plants, the concentrations of nutrients available to the plants are still not sufficient to reach yields and sizes of commercial value, unless plants are further fertilized. The reason stands in the still low densities of fish, the competition for nutrients with microalgae growing in the pond and eventually the continuous dilution of nutrients by large volumes of new water used to refill the ponds.

Aquaponics has been developed mainly within recirculating aquaculture systems (RAS) where waste water is continuously recycled and reclaimed back to fish after a biofiltration stage (Rakocy 1989; Rakocy and Hargreaves 1993; Lennard 2004) (Fig. 7.3). RAS technology was developed to overcome all the problems linked with water use and pollution from traditional aquaculture systems (open systems) in which large volumes of water are discharged to avoid the build-up of wastes and toxic metabolites (Barnabé 1990; Diana et al. 1997). Traditional aquaculture has in

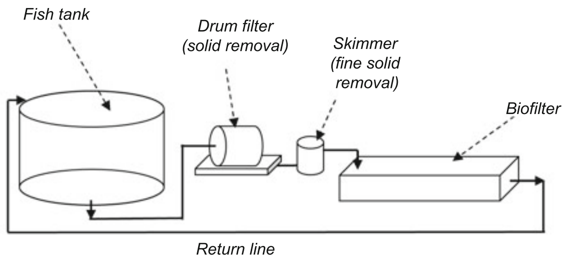

Fig. 7.3 Design of a generic recirculating aquaculture system—RAS

fact a consistent impact on the environment (Piedrahita 2003; Verdegem et al. 1999, 2006) due to the big water footprint. In addition the pollution from open aquaculture systems raises concerns about the sustainability of intensive fish farming (Costa Pierce 1996).

RAS has a very limited use of water and discharges very little amounts of wastewater (Verdegem et al. 2006). The core management of RAS focuses on the continuous reuse of water, which is possible through mechanical waste removal (uneaten feed, fish solids, dead fish) and the oxidation of nitrogen wastes operated by biological filtration (van Rijn 1996) to convert ammonia into no-toxic nitrate (nitrification).

An aquaponic system is a RAS in which the biological filtration is partly operated by plants (Fig. 7.4), whose roots host the bacteria responsible for the nitrification and directly uptake nutrients for plant growth. Aquaponics takes advantage from the nutrient build-up normally occurring in closed system due to the higher fish stocking densities and the much lower water exchange needed to get rid of fish excreta than traditional aquaculture. The increasing levels of nutrients allow aquaponics to achieve concentrations similar to chemical hydroponics and to obtain consistent productions of plants of commercial value.

The higher fish densities than traditional aquaculture is allowed by the continuous mechanical filtration to remove solids (Fig. 7.5) and the nitrification of ammonia, which prevents toxicity to fish and allow plants to take up nitrate, the most assimilable form of nitrogen. Likewise, the presence of other beneficial microorganisms such as fungi, microplankton, mineralizing bacteria, rhizobacteria help not only the system to increase the pool of essential nutrients available to plants, but also improves the resilience of the system against plant pathogens (Savidov 2005).

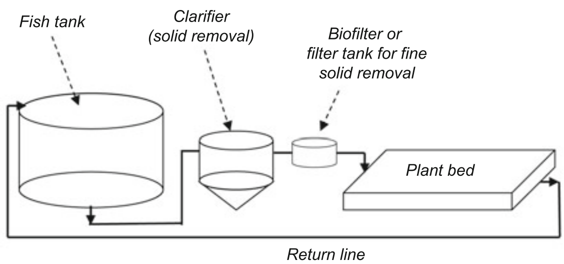

Fig. 7.4 Design of a generic aquaponic system

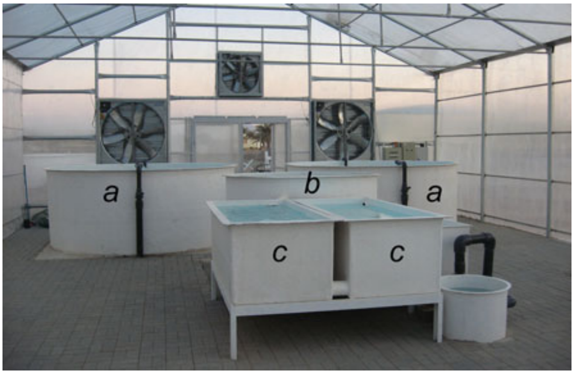

Fig. 7.5 Aquaponic system. *a* fish tanks; *b* clarifier; *c* filter tank for fine solid removal

Differences between aquaponics and RAS can be found in the simpler solid waste management, of the former, since a lower efficiency in solid removal improves the opportunities to obtain plant nutrients from the mineralization of fine suspended wastes. On the contrary RAS water must have the lowest concentrations of fine wastes to avoid any clogging of the biofilter, which eventually reduce the efficiency of the nitrifying bacteria.

Aquaponics does not differ from hydroponics for what concerns the types of systems in use: DWC (Fig. 7.6), NFT and media beds. However there are some differences in the management, since the combined presence of fish and plants requires some compromises in the setting of the environmental conditions and water parameters, which should always meet the optimum for both. This, in some cases, limits the choice of crops due to suboptimal environmental conditions of certain plants.

One constrain in aquaponics is the limited choices available in crop protection, due to the presence of fish. In aquaponics in fact no chemical pesticides can be used and even many of the remedies in use in organic agriculture may result toxic to

Fig. 7.6 Plant tanks in an aquaponic system where plants grow with bare roots

fishes. This, if on one side pull farmers to adopt mainly preventive strategies against pathogens and pests, on the other side allows for safer productions that are highly appreciated by a large number of consumers.

One recent advance in aquaponics is the use of hybrid or decoupled systems (Figs. 7.24 and 7.25), in which the fish and plant subsystems work as standalone units (RAS + hydroponics). In the former the separation between fish and plants is temporarily void to let the hydroponic unit be refilled with nutrients from fish wastewater and the RAS unit to use reclaimed water from plants; in the latter the water only goes from the fish to the plant unit. Such systems keep optimal growing conditions for both animals and plants and would give more freedom in using the traditional remedies in organic crop protection without any risks of fish toxicity.

Another difference in aquaponics stands in its complex ecosystem, in which the presence of microorganisms is not prevented but rather encouraged to improve the conversion of suspended wastes into nutrients for plants and to create a highly competitive and resilient environment where pathogens have difficulties to thrive.

In plant nutrition aquaponics supplies most of the nutrients to the plants, with the only exceptions of calcium, potassium and iron that need to be integrated through the regular addition of buffers to control the water pH into the systems. Following the natural conversion of ammonia into nitrate operated by nitrifying bacteria both aquaponics and RAS water tend in fact to acidify and need to be re-balanced by adding alkali to maintain optimal operating conditions for both bacteria, fish and plants.

Aquaponics has lower concentrations of circulating nutrients than hydroponics (Table 7.3). Despite the low levels of minerals aquaponics shows same yields of hydroponics firstly because nutrients are continuously supplied by fish to plants,

Table 7.3 Concentrations of nutrients in hydroponics compared against aquaponics at the Agriculture Experimental Station of the University of Virgin Islands (Massantini 1968; Rakocy et al. 1992, 2004a, b, 2006)

	Hydroponics			Aquaponics
	Minimum (mg L^{-1})	Optimal (mg L^{-1})	Maximum (mg L^{-1})	Average concentrations (mg L^{-1})
Nitrate	40	60–160	200	26.3–42
Ammonia		0–40	100	0.95–2.2
Phosphorus	15	30–90	130	8.2–16.4
Potassium	100	200–400	600	44–63.5
Calcium	75	150–400	600	11.9–24.2
Magnesium	25	25–75	150	6.0–6.5
Sulphur	50	75–300	600	18.3
Iron		2–4	10	1.3 –2.5
Boron		0.2–1	5	0.09–0.19
Manganese		0.2–2	15	0.06–0.8
Copper		0.01–1	5	0.03–0.05
Zinc		0.01–1	20	0.34–0.44
Chloride			600	11.5

and secondly because the water movement into the system enhances the flow of nutrients at root level and the consequent plant uptake.

7.2 Past and Present Research

Aquaponics research started to move its first steps by looking at bioremediation through the use of plants and the integration of systems for alternative productions. Initial trials focused on finding optimal component designs and assessing the most efficient fish/plants nutrient ratios and yields. Successive researches focused on the optimization of the plant nutrients in the systems and in the improvement of waste management for the full use of minerals for plant nutrition.

More recently the interest has been centred on the upgrade of the systems for commercial productions, in particular on the use of lights, decoupled systems as well as in exploring the beneficial interactions between plants and microorganism thriving into the systems.

The research on aquaponics started during the seventies. Several universities across North America and Europe started testing fish with plants in closed systems (Naegel 1977), but with designs of components still at their primordial stage. Since the eighties many researchers developed extensive studies on aquaponics with the focus on the component ratio. Prof. James E. Rakocy dedicated three decades on aquaponics at the University of the Virgin Islands (UVI), USA where he built and managed a commercial-scale system (Fig. 7.7). He was among the first to identify the optimal balance between fish and plants and to optimize the components for floating systems. In Australia Dr. Wilson Lennard carried out trials with an extensive number of plant species, optimized fish/plant ratios and compared the performances from different system designs. In Canada Dr. Nick Savidov pioneered research on improved mineralization for UVI systems in greenhouses in cold climates.

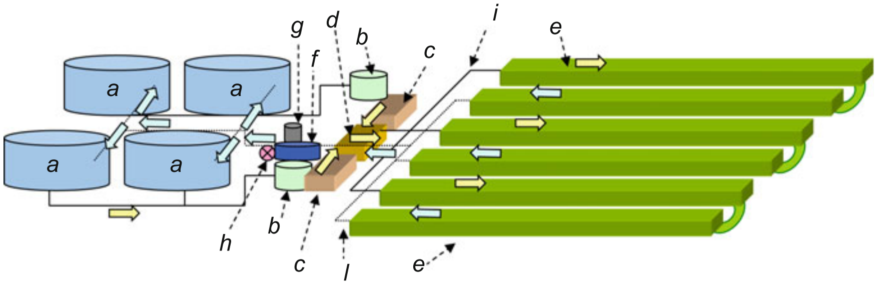

Fig. 7.7 Diagram of the UVI system: ***a*** fish tank, ***b*** clarifier, ***c*** filter tank, ***d*** degassing unit, ***e*** plant tanks (floating system), ***f*** sump, ***g*** base addition tank, ***h*** water pump, ***i*** influent water from the degassing tank to the plant tanks, ***l*** effluent water from the plant system to the sump

7.2.1 The UVI System

The University of the Virgin Islands (UVI) has been the first academy to test a pilot system for both research and commercial production (Fig. 7.7). The system, still in full activity, has four fish tanks accounting for a total volume of 31.2 m^3, two conical clarifiers of 3.8 m^3 each, four filter tanks of 0.7 m^3 each, which are used to remove fine particles through orchard nets, and a degassing tank where the intense aeration occurring removes carbon dioxide from the water before it goes to the plant tanks. The fish unit supply fertilized water to six hydroponic tanks 30.5 m long 1.2 m large and 0.4 m deep that account for a total surface of 214 m^2. Water from the plant tanks is collected into a sump where is pumped back to the fish tanks after being buffered by a small base addition tank. The total water volume of the system is 110 m^3.

Water is circulated by means of a ½ hp water pump that guarantee for a mean retention time of 1.5 h in the fish tanks. The system is supplied by two blowers, one of 1.5 hp for the fish tanks, and another of 1 hp for the plant troughs.

The UVI system can produce approximately 3 tons of tilapia and 11 tons of lettuce a year from a total surface of 400 m^2.

7.2.2 Fish Species

Aquaponics was tested with several fish species, which testimonies the large versatility of this system to different climatic conditions. The species cultured were tilapia (*Sarotherodon aurea*, *Oreochromis niloticus*, *Tilapia rendalli*) (Watten and Butsh 1984; Rakocy and Hargreaves 1993; Rakocy et al. 1999a, b; Seawright et al. 1998), African catfish (*Clariar gariepinus*) (Endut et al. 2010; Pantanella et al. 2011a) Murray cod (*Maccullochella peelii peelii*) (Lennard and Leonard 2004), rainbow trout (*Oncorhynchus mykiss*) (Adler et al. 2003), common carp (*Cyprinus carpio*) (Naegel 1977) Asian Barramundi (*Lates calcarifer*) (Rakocy 2007), mullet (*Mugil cephalus*) (Pantanella et al. 2011b) Eurasian perch (*Perca fluviatilis*) (Graber and Junge 2009), largemouth bass (*Micropterus salmoides*) (Pantanella, unpublished data) and bester sturgeon (*Acipenser ruthenus* × *Huso huso*) (Dediu et al. 2012).

At commercial level tilapia is the most reared fish in aquaponics systems, followed by ornamental fish, perch, bluegill, trout, bass and, for a certain number of farms, barramundi, carp, Pangasius and crayfish (Love et al. 2015).

7.2.3 Feed/Plant Ratios

As previously mentioned one of the primary objectives of research was to find optimal feed/plant ratios to determine the essential management criteria of the

Table 7.4 Daily nitrogen and phosphorus sink per plant according to different studies

Type of crop	Nitrogen sink (g m^{-2} day^{-1})	Phosphorus sink (g m^{-2} day^{-1})	Author
Lettuce	0.83	0.17	Gloger (1995)
Lettuce	0.94	0.1	Alder (2003)
Lettuce	1.0–1.1	na	Dediu et al. (2012)
Lettuce Sweet basil	0.13–0.32 0.34–0.51	na na	Pantanella et al. (2012b)
Aubergine Tomato Cucumber	3.3 0.6 0.4	0.4 na 0.1	Graber and Junge (2009)
Salsola	0.2–0.4	na	Pantanella et al. (2011b)

Table 7.5 Feed to plant ratio determined from past researches

Type of crop	Daily amount of feed (g m^{-2})	Feed crude protein (%)	Fish species	Author
Lettuce	56	32	Tilapia	Rakocy et al. (1997)
Sweet basil	81–100	32	Tilapia	Rakocy et al. (2004a)
Lettuce	33	43	Murray cod	Lennard (2004)
Water spinach	15–42	32	African catfish	Endut et al. (2010)

systems from its many variables: feed quantity, feed protein content (percentage of crude protein, %CP), type of plant cropped, environmental conditions and type of aquaponics system. At the University of Virgin Island (UVI) Rakocy et al. (1992) determined that 2.4 g day^{-1} of feed with 36% protein to tilapia could supply nutrients to one plant of lettuce grown on floating system.

An approach in mass balance used the daily plant nutrient uptake (Table 6.4), mainly with a focus on the sink needed for wastewater treatment, although it is worth reminding that the nutrient sink in plants sensitively vary among species/varieties and environmental conditions, which eventually affect the growth rate and yields of the plants.

On the other hand a reference on the amount of nutrients released by feed was also given by Graber and Junge (2009) who calculated that 1 kg fish feed at 45% CP eaten by tilapia could supply 46 g of nitrogen, 6.0 g phosphorus and 1.0 g potassium (Table 7.4).

Trials carried out during the years gave more practical feed ratios, which are based on the amount of feed needed to supply nutrients to plants growing at standard densities (i.e. 20–30 plants for leaf vegetables) (Table 7.5).

As said earlier the feed ratios depend on the crop being cultivated, the type of system, and the environmental and climatic conditions. These parameters can sensitively affect the nutrient availability for the plants: from 60 to 100 g m^{-2} day^{-1} (Rakocy et al. 2006) for the standard UVI-type systems down to 16 g m^{-2} day^{-1} for lettuce growing in systems with minimum denitrification and additional waste mineralization provided by offline tanks where solids are kept continuously oxygenated (Lennard 2013).

Based on projects' experiences FAO delivered rule of thumb feed to plant ratios: 40–50 g m^{-2} day^{-1} for leaf vegetables and 50–80 g m^{-2} day^{-1} for fruiting vegetables (FAO 2014).

Plant uptake can be increased by the type of system in use (Lennard and Leonard 2006), since deeper contact of roots in the nutritive solution eases the absorption of nutrients. In trials using different beds the growth of plants was higher in deep water culture (DWC) and nutrient film technique (NFT) because of the wider root exposure to the nutritive solution (Pantanella et al. 2012c). Nevertheless the resulting higher nitrogen sink was not due to higher concentrations of nutrients accumulated in the plant tissues, which were constant, but rather from the increased biomass obtained by the plants. Good nutrient sink is therefore the result of yield maximization in which optimal vegetable biomass growth is obtained.

7.2.4 Nutrient Concentrations in Aquaponics

In aquaponics the levels of nutrients are in general much lower than hydroponics. At the University of the Virgin Island Experimental Station (UVI) (Rakocy et al. 1992, 2004a, b, 2006) aquaponic vegetables were cropped with only a small percentage of the optimal hydroponic concentrations (Table 6.3): nitrate ($N\text{-}NO_3$) 16–70%, ammonia ($N\text{–}NH_4$) 0–5.5%, phosphorus (P) 9–55%, potassium (K) 11–32%, calcium (Ca) 0.4–16%, magnesium (Mg) 8–25%, sulphur (S) 6–24%, iron (Fe) 32–100%, manganese (Mn) 3–40%. Higher concentrations of nitrogen than those measured at UVI are possible and can easily reach levels similar to hydroponics. Nevertheless, yields and quality of lettuce heads from aquaponics are similar to hydroponics even at concentrations ten times lower than those in use in hydroponics (Pantanella et al. 2012a). Nitrate concentration in RAS can vary from 100 to 1000 mg L^{-1} (Van Rijn 2010), thus resulting in more than sufficient levels of nutrients for commercial production of plants. However, some attention must be also put in the optimal nitrate concentrations for fish since different growth rates or toxicity responses are seen depending on the fish species. Losordo et al. (1998) noted that fish can tolerate nitrate levels of 200 mg L^{-1}, but concentrations above 300 mg L^{-1} appear to bring some toxicity (Masser et al. 1999). Likewise, trials done with African catfish demonstrated a decrease of growth and increase of nitrate in the plasma for concentrations in the water above 140 mg L^{-1} (Schram et al. 2012). Marine fishes are also less tolerant to high nitrate concentrations than freshwater fishes.

In aquaponics there are some plant limiting nutrients, which are not adequately supplemented by the fish feed. Main deficiencies are found in iron, potassium and calcium (Rakocy et al. 1993). However, calcium and potassium can be supplemented to aquaponic systems in the form of calcium carbonate, potassium bicarbonate, calcium hydroxide and potassium hydroxide in order to raise the pH or to increase the alkalinity in water (Rakocy et al. 1993), which is consumed by the nitrification process.

Resh (2004), Leoni (2003) and Sonneveld and Straver (1989) indicated optimal nutrient concentrations for plants. Nevertheless, the nutrients' needs vary according to the growth stage of each plant (Leoni 2003), which can be a challenging factor in aquaponic systems because of the difficulties in quickly adjusting the pool of minerals in systems containing big volumes of water or without stressing the fish. Van Anrooy (2002) remarked that high concentration of nitrates favours vegetative growth but lower levels of nitrogen are required during the fruiting stage.

Equal concentrations of nitrogen and potassium (N:K ratio of 1:1) bring cucumber productions to same or higher yields than hydroponics (Savidov 2005; Pantanella, unpublished data), while higher N:K ratios apparently reduce fruit yields (Graber and Junge 2009). The low concentrations of potassium is a limiting factor in fruity plants, as this element is essential in fruit setting, ripening and sweetness. Reductions of N:K ratios can be obtained by either buffering the system with alkali (potassium hydroxide, potassium bicarbonate) or by increasing the denitrification in dedicated tanks of the system, thus letting nitrogen in the water to be eliminated into the atmosphere (Rakocy, personal communication 2008).

7.2.5 Water Parameters

In aquaponics the nutrient availability is affected by pH (Rakocy et al. 2006; Losordo et al. 1998, Tyson et al. 2004). Values of pH of 7–8.5 favour nitrifying bacteria and thus improve the efficiency in the elimination of ammonia from the water (Tyson et al. 2008), however such higher levels may affect macro and micronutrient availability outside the pH range of pH 5.5–6 that is considered optimal for plants (Jones 1997; Resh 2004; Tyson et al. 2008).

Other relevant water parameters are found in electrical conductivity, which should range between 2.00 and 4.00 dS m^{-1} or less to avoid plant/leaf phytotoxicity (Resh 2004; Rakocy et al. 1992, 2006); alkalinity above 100 mg L^{-1} for optimal nitrification buffering (Rakocy 1997); biologic oxygen demand (BOD) below 20 mg L^{-1}, dissolved oxygen (DO) above 5 mg L^{-1} both for optimal fish, plant growth and development of nitrifying bacteria. Low BOD and high DO is needed to avoid oxygen depletion by aerobic bacteria and the creation of anaerobic conditions that could harm fish due to the production of hydrogen sulphide, an extremely toxic gas for fish (Rakocy 1997).

7.2.6 Water Use in Aquaponics and Recirculating Systems

The water consumption in aquaponics includes both fish and plant management. Replacement takes into account the discharge of sludge from fish faeces and uneaten feed, the plants evapotranspiration, the accumulation of water in the plant tissues, the water evaporation from fish tanks as well as other variable losses depending on the system design (evaporation from airstones bubbles, water splashes from pipes, etc). Researches have assessed in 0.5–4.6% of the total aquaponic system volume the daily amount of water consumed that needs to be added (Naegel 1977; Watten and Buschs 1984; Mc Murty et al. 1997; Rakocy et al. 1997, 2004a; Savidov 2005; Al-Hafedh et al. 2008). Nevertheless such water consumption is in the lower part of the above range in greenhouses or in systems with advanced aeration systems that keep the water evaporative losses to a minimum.

More practical information refer to the amount of water required to grow one kilogram of fish, which has been determined in 0.5–1.4 m^3 kg^{-1} in intensive RAS, while increasing consumption patterns in traditional aquaculture are observed depending on the management intensification: from 4.7 to 7.8 m^3 in aerated ponds, 11.5 m^3 in extensive ponds, up to 30 m^3 in aerated pond with water exchange (Verdegem et al. 2006).

As already mentioned water use in aquaponics is affected by the additional evaporative losses from the plant system. However a correct account of water consumption in aquaponics must consider the break-even of nutrients in which minerals are maintained at constant concentrations as the result of the equilibrium between the nutrients released by the feed/fish, the losses of nutrients from solids removed or denitrification, and the minerals directly used by plants and roots.

An assessment carried out in UVI-type systems (Pantanella et al. 2012b) showed that for one kilogram of tilapia (*Oreochromis niloticus*) body weight gain (equivalent to 1.0–1.2 kg of feed with 40–43% CP) the water consumption at nitrogen break-even point is 637–1373 L, and is balanced by 11–25 kg of lettuce sink. On the other hand the growth of one kilogram of African catfish (*Clarias gariepinus*), equivalent to 1.0–1.3 kg of feed with 40% CP, requires 243–395 L of water when growing 5–6.5 kg of sweet basil (Pantanella et al. 2012b). Therefore, the water consumption in aquaponics is affected by the type of crop, because plants capable of stocking more nitrogen in their tissues would eventually require less biomass to keep the nutrients into the aquaponic systems at a steady level, which eventually results in lower water volumes needed to grow plants.

However, the water consumption between aquaponics and hydroponics is 70–130% higher in UVI-type systems due to the presence of extended water surfaces from the fish tanks and the intense aeration occurring to keep fish with sufficient dissolved oxygen. Such increments suggest for the adoption of specific design solutions to further reduce the evaporative losses (e.g. bubbling) wherever water supply is an issue (Pantanella et al. 2012b).

7.2.7 Aquaponic Yields

Aquaponic/hydroponic plant production show higher yields than conventional soil crops. Resh (2004) stated that soilless cultivation could at least double the yields of conventional horticultural plants: from 1 kg m^{-2} in soil to 2.3 kg m^{-2} in soilless for lettuce; from 1.2–2.4 kg m^{-2} in soil to 14–74 kg m^{-2} in soilless for tomato. Rakocy et al. (1992) showed yields of 4.35 kg m^{-2} from lettuce grown at 25 plants m^{-2} in 21 days. On the advantages of aquaponics against soil production Mc Murty et al. (1990) showed higher yields with cucumber (7.3 vs. 4.6 kg m^{-2}) but lower production with tomato (4.6 vs. 6.1 kg m^{-2}). Rakocy et al. (2004a, b) showed higher productivity in basil with yields of 1.8–2.0 kg m^{-2} (0.6–1.0 kg m^{-2} in soil) and okra with 2.5–2.9 kg m^{-2} (0.15 kg m^{-2} in soil). The use of the aquaponic concept, with higher nutrients in the water and its recirculation between a fish tank/basin and rice could enhance rice production by 66% against traditionally fertilized rice, with yields per crop of 8.5 ton ha^{-1} against 5.1 ton ha^{-1} (Pantanella et al. 2011c).

Aquaponics shows higher productivity than hydroponics in mature systems for either tomato (31–59 vs. 41–45 kg m^{-2}) and cucumber (42–80 vs. 50 kg m^{-2}) and whenever the N:K ratio is close to 1 (Savidov 2005). For higher N:K ratios certain fruity plants can still perform well against hydroponics, as in the case of aubergine (7.7 kg vs. 8.0 kg m^{-2}) and tomato (23.7 vs. 26.3 kg m^{-2}), but cucumber seems to shows reduced performance (3.3 vs. 5.2 kg m^{-2}) (Graber and Junge 2009). Nevertheless N:K ratio at 1 even with lower nutrient concentrations than hydroponics (up to three time lower) can provide similar yields (7.6 vs. 7.5 kg m^{-2}) and quality of fruits (sweetness, vitamin C) in cucumber (Pantanella, unpublished data). For leaf vegetables there are no differences between aquaponics and hydroponics for both lettuce and basil productivity and quality (Pantanella et al. 2010, 2011a, 2012a). However concentrations of nitrates above 20 mg L^{-1} should be maintained to secure good growth and greenness in leaves. In saline crops, such as salsola aquaponics shows sensitive advantages than hydroponics even at lower nutrient concentrations (Pantanella 2011b). However, the best growth responses for both plants and fish should take into account the most favourable nutrients balances and climatic conditions, which must be adequate for the species being produced into the systems.

Aquaponic sub-systems design (floating system, gravel, NFT) could also help to raise plant yields and to increase water quality. Lennard and Leonard (2004) outlined the enhanced nitrification obtainable from gravel systems and, at the same time, the potential buffering capacity of gravel. Rakocy et al. (2006) also confirmed that substrates in the form of sand and gravel are optimal, but care should be put in delivering solid free water to avoid clogging. Media however present some drawback because it requires more maintenance to grow plants (e.g. digging holes during transplant) or because it may bring some stem damages wherever aquaponics is developed in windy outdoor conditions (Rakocy et al. 2006).

7.2.8 Economics

Economic assessment from literature showed high profitability of aquaponics leaf vegetables than fruit productions. Mc Murty et al. (1997) projected annual yields of

41.5–54 kg m^{-3} of tilapia and 29.2–59.6 kg m^{-2} of tomato, which was respectively equivalent to 109–142 USD m^{-3} and 50–102 USD m^{-2} depending on the system design. However Rakocy outlined that the biomass harvestable from each crop of Nile tilapia is 61.5 kg m^{-3} and 70.7 kg m^{-3} for red tilapia (Rakocy et al. 2004b). Savidov (2005) estimated a gross return of 342 USD m^{-3} every 24 weeks from tilapia reared in tanks (sold at 5 USD kg^{-1}), while basil returns were 184–236 USD m^{-2} per year (price of basil 15.4 USD kg^{-1}). Rakocy et al. (2004a) estimated a gross revenue of 515–550 USD m^{-2} from aquaponic basil against a revenue of 172 USD m^{-2} from soil. The experience from researchers and commercial scale operators shows how the highest incomes come from the vegetable side of the aquaponic systems, with nearly 3-fold gains than fish (Savidov 2005). A recent survey among commercial aquaponics operators showed that the average size of farms has an acreage of 0.01 ha, with the median respondents investing 5000–9999 USD and reporting profits in nearly 40% of cases (Love et al. 2015).

7.3 System Components and Management

A standard aquaponics system (Figs. 7.4 and 7.7) is constituted by fish tank/s, a mechanical filter to remove settable solids (fish faeces, uneaten feed) and suspended solids, a biofilter (optional, depending on the type of plant grow system used) to convert the ammonia excreted by fishes into nitrate through nitrification, and plant trough/s. Aquaponics can also have a sump where water from the plant troughs converge and is added with buffer from a dedicated buffer addition tank.

Aquaponics follows the evolution of the systems occurred during almost forty year of applied research carried out by scientists worldwide. Most of the current designs are built following the original outline developed by Professor James E. Rakocy at the University of the Virgin Islands, who started working on the integration of plants and fish since the late seventies. Through the years Professor Rakocy and his team designed a commercial scale system with appropriate component ratios based on optimized nutrient balance between fish and plants (Fig. 7.7).

7.3.1 Fish Tanks

Fish tanks follow the engineering of recirculating systems. The design should allow the solids to be quickly removed to maintain good water quality. The ideal shape is circular as water rotates with no turbulence towards the centre of the tank where the drain is. In terms of design the ideal radius-to-height ratio in circular tanks is 3:1–4:1, this allows centripetal forces to bring the solids towards the central drain. To further improve the self-cleaning capacity a slope towards the centre is suggested to help the solids to move and settle towards the centre of the tank. Other designs are possible, with raceways leading the options for their good space use and cleaning efficiency. Squared tanks are used, but the presence of corners creates death spots where wastes accumulate, especially in flat bottomed tanks. Therefore the highest solid removal efficiency must be always guaranteed.

The most common material used for fish tanks is fiberglass (Fig. 7.8) for its versatility to be used for wide recipients. However, it is the most expensive option and may be used for systems with a very long lifespan. Other material used, mainly for small volumes of water is HDPE/LDPE, which is moulded for 0.1–5 m^3 tanks. Alternatively HDPE or EPDM liners can be used for either backyard or commercial scale systems. Thick liners of 0.75–1 mm can be welded to make bigger containers and are fairly resistant to mechanical stress. Liners can be a very cheap option to cover metal or wooden/bamboo walls or iron-meshed frames (Fig. 7.9). Alternatively liners can be used for ponds, providing that good water circulation and drainage is guaranteed to efficiently remove the solids. A suitable solution for backyard systems is the intermediate bulk container (IBC) (Fig. 7.21), which is used to transport liquids, is fairly resistant and of adequate volume to host up to 15–20 kg of fish serving 2–4 m^2 plant area.

The tanks vary in stocking densities depending on the species reared and on the aeration-oxygenation technology. In general the density is chosen according to the

Fig. 7.8 Fiberglass tanks

Fig. 7.9 Fish tanks made of liners and bamboo stakes

oxygen concentration in the water, which is replenished by either new incoming oxygenated water or by aeration/oxygenation inside the tank.

The more sensitive to oxygen is the fish species the more water exchange or aeration-oxygenation is needed to support the animals' needs. Alternatively the fish stocking density must be reduced to maintain adequate dissolved oxygen concentrations. In general for tilapia 80–90% oxygen saturation can be sustained by standard aerators up to a fish density at harvest of 60–70 kg m^{-3} under a hydraulic retention time of 1–1.5 h. Higher stocking densities or higher saturation are possible providing that pure oxygen is supplied.

Water exchange in tanks is also important to wash solid out and to dilute the ammonia excreted by fish, which is successively oxidized by the biofilter into less harmful nitrate. Ammonia is harmful to fish at concentrations as low as 1 mg L^{-1}, but its toxicity depends on the pH, since acid conditions in water bring ammonia into its ionized and less toxic form, ammonium. On the contrary levels of pH above 7 increase the concentration of the unionized form thus resulting dangerous for the fish.

In commercial aquaponic systems tanks are mainly managed with a staggered production of same-size fish stocked in each tank. Staggered management allows to:

- Harvest one tank of same-size fish at one time
- Have a continuous supply of fish to the market depending on the number of tanks available
- Maintain a fairly constant fish biomass into the whole system, which eventually keeps constant the levels of nutrients for plants
- Avoid peaks in fish biomass into the system, which eventually result in excessive oxygen consumption and high ammonia production.

7.3.2 Mechanical Filtration

Solid removal is a fundamental part of any recirculating system. Solids are formed from fish excreta and uneaten feed and must be removed efficiently and quickly, to prevent them from releasing ammonia into the water or to create anaerobic spots that bring to the production of hydrogen sulphide, a very toxic gas for fish. In any recirculating system the presence of solid reduces the efficiency of the aeration/oxygenation, due to the increased oxygen consumption from mineralizing bacteria, which use dissolved oxygen to digest the wastes (biological oxygen demand, BOD).

Nevertheless, in aquaponics the efficiency in removing solids can be lower than RAS, because the presence of small quantities of fine suspended solids would add more nutrients to the plants trough mineralization. On the contrary RAS systems need to remove as much fine solids as possible to prevent any risk of clogging of the biofilter, which would deteriorate the water quality dramatically.

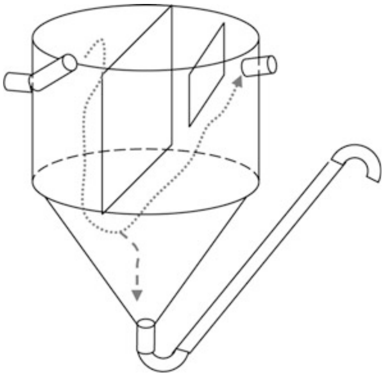

Fig. 7.10 Clarifier with central baffle

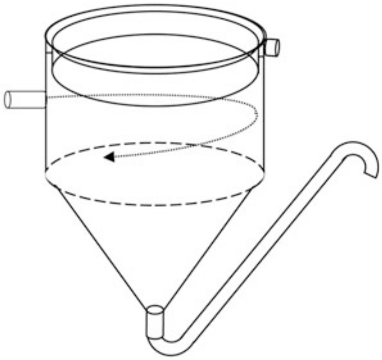

Fig. 7.11 Swirl separator

The most common solid removal devices are: clarifiers, swirl separators, radial flow clarifiers and drum filters. Clarifiers (Fig. 7.10) are conical-bottomed tanks where solid settle by gravity under a water retention time of 20 min (Rakocy 2007). In general the removal performance is 59%. On the other hand swirl separators (Fig. 7.11) use centrifugal force to settle solids but they seem to have lower removal efficiency (37.1%) than radial flow clarifiers (77.9%) (Fig. 7.12) (Davidson and Summerfelt 2005). Both systems have been already used in semi-commercial aquaponic systems with positive results.

Drum filters are the most used devices in RAS. Water is filtered through a micro screen of variable size (50–100 μm) in which solids are firstly trapped and then removed by a backflush of water that pushes the dirt out, through a dedicated outlet. Although very efficient, drum filters are not universally adopted in aquaponics due to economic reasons and because of the excessive removal of solids that sensitively reduce the pool of nutrients obtainable from fine wastes. Another technology use geotextiles to get rid of flocculated wastes. In this case concentrated sludge from an offline tank is mixed with an organic polymer that binds solid particles and precipitate them. The precipitate is then squeezed from the water into a permeable bag and successively removed once the bag is full.

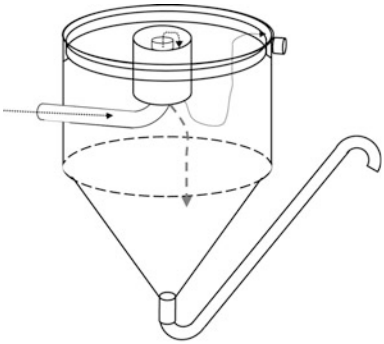

Fig. 7.12 Radial flow clarifier

Fig. 7.13 Clarifiers with 60° conical bottoms

Regardless the system solids need to be efficiently removed to prevent that they clog plant roots and increase the biological oxygen demand of the system. The overload of the system with solids is in fact negative because of the risks of anaerobic spots and hydrogen sulphide production. On the other hand moderate quantities of fine solids allow more nutrients to be released into the water through mineralization. This balance between fine solid removal and mineralization brought to different management strategies among aquaponic systems around the world.

In the UVI system (Fig. 7.7) fine solids escaping the clarifier (Fig. 7.13) are trapped in a filter tank made with orchard net (Fig. 7.14). At this stage most of the suspended solids settle on the mesh and become a growth substrate for the aerobic bacteria that produce biofilms. The increasing volume of the adhered solids and biofilm is periodically controlled by washing the nets to remove all the organic matter. The frequency of the washing of the nets is eventually used to create a controlled anaerobic environment (Rakocy 2008, personal communication). The increase of organic matter and aerobic bacteria on the nets brings in fact to an exploitation of the concentration of oxygen in the water that reach values next to zero, which favours organisms that thrive in oxygen-free conditions (anaerobiosis). In such condition denitrifing bacteria, which are anaerobic organisms, consume the nitrate nitrogen in the water and release nitrogen gas into the atmosphere. This controlled anaerobic process is important in the overall nutrient management of aquaponics because it keeps nitrogen to constant levels into the system, or even decrease it to adjust the N:K ratio to more favourable numbers for fruity plants. As mentioned in the previous section N:K ratios of 1 are optimal for fruits' settings and ripening, thus the overall reduction of the nitrogen in the water helps potassium to become relatively predominant. Being the anaerobic stage a critical condition due to the production of hydrogen sulphide gas, it is very important to intensively de-gassing the outgoing water before circulating back into the system.

In Canada the solid management follows a more intensive approach, in which the complete mineralization of the wastes is pursued. The rationale is that wastes contain good sources of nutrients that need to be released in order to supply optimal fertilization to plants. The systems make use of oxygen gas to supersaturate the water thus allowing both dissolved oxygen and oxidizing bacteria degrade the organic matter into simpler components that are used by plants.

A simpler approach makes use of media beds of adequate granulometry to mineralize the fine suspended particles. The media is contained in tanks that are constantly flooded and drained with the aquaponics water. The most common beds are made of inorganic substrates such as volcanic tuff, gravel, pumice, expanded clay. The media increases the surface available for oxidizing microorganisms to thrive and to degrade the organic matter into its simpler elements. The constant and regular flooding and draining of the media allows water and air to reciprocally penetrate the interstices and pores of the substrate and to supply with oxygen, water and nutrients the rich micro fauna.

7.3.3 Biofiltration

Biofiltration is the fundamental component of any recirculating system. As mentioned in the previous sections fishes release ammonia from their metabolism, and the concentration of released ammonia increases with the percentage of proteins contained in the feed. Ammonia concentrations would raise quickly due to the high densities of fish and the abundant feeding, thus resulting in the risk of toxicity and death of fish. Concentration as low as 1 mg L^{-1} are harmful especially if the pH in the water is basic, since ammonia would be in its unionized and more toxic form. To maintain good water quality it is necessary to oxidize this by-product into the less harmful nitrate. Two main bacteria species help to run this process: *Nitrosomonas* and *Nitrobacter*, the former oxidizes ammonia into nitrite, the latter nitrite into nitrate.

Fig. 7.14 Filter tanks to capture fine solids by means of orchard type nets

1. *Nitrosomonas:* Ammonia (NH_3) → Nitrite (NO_2^-)
2. *Nitrobacter*: Nitrite (NO_2^-) → Nitrate (NO_3^-)

These beneficial bacteria establish their colonies on every surface of the systems. They need both good water circulation to allow new ammonia molecules to come into contact with the colonies and good oxygenation to allow the prompt oxidation of ammonia.

Biofilter is any media that has a large surface per unit of volume (specific surface area—SSA) to let bacteria adhere over a large area. The biofilter presence in aquaponics system is facultative. The UVI system does not use any specific biofilter unit, but leaves to the system's surface in contact with water (the tanks, the submerged part of floating rafts, the pipes, the plant roots) the task to host nitrifying bacteria. The presence of biofilter is however suggested, if not recommended, to help the system to be more resilient against ammonia peaks or sudden changes from the optimal environmental conditions for nitrifying bacteria (temperature, salinity, oxygen). Common media used in both RAS and aquaponics are: bioballs, spherical plastic media with voids in the inside and a SSA of 600 m^2 m^{-3}; plastic beads that can reach SSA up to 1400 m^2 m^{-3}. Biofiltration in aquaponics can be also provided by media beds, whose substrate used to support the plants can also host nitrifying bacteria. Common media used is gravel (150–200 m^2 m^{-3}), volcanic tuff (300 m^2 m^{-3}), and expanded clay (200–250 m^2 m^{-3}). The correct sizing of the biofilter depends on the maximum feed intake of the fish stocked and the resulting ammonia produced. The optimal sizing also take into account of the climatic conditions, dissolved oxygen, salinity, pH and the type of biofilter media used with its specific SSA.

The bacteria in the biofilter work within optimal ranges of temperature (17–34 °C), good dissolved oxygen (>5 mg L^{-1}) low salinity, low dissolved solids. Such environmental conditions should adjust to the optimal of the plants and fish being cultured. Plants for example prefer pH ranges of 5.5–6.5, a level in which all the micronutrients for plants are in their maximum soluble form. On the other hand the higher temperatures required by bacteria do not perfectly match the optimal temperatures of certain vegetables. It is then necessary to find some compromises, being aware that the biofilter should be then oversized to compensate for the suboptimal working conditions of nitrifying bacteria.

7.3.4 Mineralization

Mineralization is the second most important microbiological process in the aquaponics system. It implies the progressive degradation of organic wastes into smaller components, the process releases nutrients otherwise not available to plants.

Many organisms are involved in mineralization: worms, nematodes, protozoa, fungi, bacteria. Each decomposer is involved in one step, to degrade wastes from bigger into smaller particles. In an aquaponics system it is common to spot the complex fauna and micro fauna degrading the organic matter, especially in substrate beds, in which the fine suspended solids accumulate and are degraded. The substrate beds, with their flood and drain cycles allow the decomposers to access air and at the same time capture new organic matter from the circulating water.

The process of mineralization requires oxygen to provide molecular oxidation and to let decomposers breath. This means that additional aeration should be provided to the system to maintain good dissolved oxygen.

During the mineralization proteins are degraded in amino acids and successively digested by bacteria that release nitrogen. However, plants can directly take up amino acids as well as any inorganic nitrogen form, with the exception of nitrogen gas. The mineralization of phosphorus is important because this element is not mobile and easily available. Mineralization converts organic phosphorus into phosphate (PO_4^-), which is assimilated by plants.

The mineralization is possible within the carrying capacity of the system. Too much waste is dangerous if not supported by the decomposers and by an adequate supply of oxygen, as it would build up into the system with the risk of anaerobic spots and the production of hydrogen sulphide.

7.3.5 Plant Beds

Plant beds in aquaponics mainly follow the same designs of hydroponics with the only difference that nutrients are not distributed by computers controlling the release of fertilizers from tanks into the circulating water, but simply by fish wastewater.

Fig. 7.15 DWC with tomato plants

7.3.5.1 Deep Water Culture

The most used plant bed is the floating system or deep water culture (DWC). In DWC water flows in long tanks of variable width (Figs. 7.6 and 7.15). The height of the water in the tank is 25–40 cm. In DWC plants float on polystyrene rafts with bare roots (Fig. 7.16), and access the nutritive solution through holes made on the floating sheets. The presence of fixed holes make the raft not flexible to adjust to different densities. A proper fish-to-plant ratio is maintained. In the case of the UVI system the surface ratio between plant beds and fish tanks is 7.3:1, while the volume ratio is 1:3.4 with an average fish-biomass-to-cultivable-area equivalent to 4 kg m^{-2} (Rakocy 2007). In DWC an intense aeration actively enhances the plants uptake by increasing the nutrient flow at root levels and by providing oxygen to nitrifying bacteria that convert ammonia into nitrate. Given the big volume of water the system requires more energy for pumping than any other types of aquaponic systems. On the other hand the big volume of water makes the system more resilient against ammonia peaks (dilution effect), while nutrients can accumulate into the water and serve the plants over a long period of time, even if fish biomass is consistently reduced or not present. Another advantage of DWC is in the thermal inertia of the system due to the big volume of water, which keeps the water under constant temperatures and prevents fish stress.

Fig. 7.16 Particular of bare roots in DWC

Advantages	Disadvantages
• Easy set up using plastic liners	• Need of food grade liners
• Suitable for outdoor as well as indoor	• Heavy system, not suitable for roof-top agriculture
• Buffering capacity of ammonia through dilution in a large volume of water	• The liners are prone to punctures if not thick enough
• Stable water temperatures	• The systems need longer periods of time to reach adequate concentrations of nutrients
• High quantities of nutrients diluted in the water	• Construction costs may be higher if materials are not easily available (polystyrene rafts)
• Systems can produce for a limited period of time with few or no fish	• Polystyrene rafts degenerate quickly under UV if not protected with paint
• Highest productivity compared to other growth beds	• Large amount of water to be pumped, higher cost of energy than other beds
• Biofiltration surface provided by floating rafts	• More expensive water sterilization to comply with water safety regulations due to the water volume
• Simple management of rafts that can be pushed to one end of the tank for easy harvest	• Not suitable for some fruit crops and root crops
• DWC can host additional species of aquatic animals to improve productivity	• Tanks can breed mosquito larvae, control is needed
• Plants do not wilt in case of black out	• Tilapia damage crops if fry colonize the plant beds
• Easy maintenance for cleaning	

7.3.5.2 Dynamic Root Floating Technique (DRFT)

The dynamic root floating technique is a variant of DWC with a shallower water column. DRFT is also called Taiwanese system and is quite widespread in South East Asia. DRFT is built on tables of variable lengths (Fig. 7.17) and has a water depth of just few centimetres (4–8) (Fig. 7.18). The rafts float like in DWC, but the presence of ridges from the bottom make it possible to decrease the water level and create an air chamber when the rafts settle on the top of the ridges. Air chambers increase air circulation at root level, prevent risks of rotting in plants and help the system to cool down the water during hot seasons, which is ideal in hot climates.

Fig. 7.17 DRFT in outdoor

The DRFT has considerable advantages against both traditional DWC and NFT, firstly because of its lighter weight than DWC that allows its use on rooftops, and secondly due to the presence of the polystyrene rafts and the air chamber underneath, which prevent any diurnal overheating of the circulating solution that constitutes one of the biggest issues in NFT instead (plant bolt and fish get stressed for extreme variations of day/night temperatures). Although not very commonly adopted, the system has been used by the author for three years with yields similar to traditional aquaponics DWC.

Fig. 7.18 The shallow water level in DRFT

Advantages	Disadvantages
• Easy set up using plastic liners on tables	• Need of food grade material
• Good for either small scale or commercial scale	• Higher cost of setting than DWC due to the presence of supporting structures
• Suitable for outdoor	• The liners need to be thick to avoid punctures
• Suitable for roof-top agriculture	• Proper care should be put in action to prevent polystyrene rafts from being damaged by UV light
• Moderate buffering capacity of ammonia through dilution in the water	• Rafts do not provide surface for nitrifying bacteria when suspended on the water
• Insulating effect from polystyrene rafts	• Lesser buffering capacity of ammonia through dilution than DWC due smaller volume of water
• Additional cooling due to the air chamber	• Not suitable for certain fruit crops and root crops
• Lower root disease risks due to the presence of air	• Tanks can breed mosquito larvae, control is needed
• Passive aeration by the presence of air chamber	• Tilapia damage crops if fry colonize the plant beds
• Higher concentrations of nutrients than DWC	• Need additional biofiltration due to the reduced surface and smaller volume of water than DWC
• System is resilient to black outs	
• Easy maintenance for cleaning	
• Water sterilization possible for food safety rules	
• Suitable for all types of leafy vegetables	

7.3.5.3 Nutrient Film Technique—NFT

The nutrient film technique—NFT is the most common system in hydroponics and the most used in aquaponics together with DWC. Like hydroponics the plants are placed in holes drilled on plastic pipes (Fig. 7.19 and 7.20) in which water flows in a shallow film to wet the roots. Given the small volume of the circulating water NFT is in general associated with a mechanical filter and a biofilter to efficiently remove wastes and convert the ammonia released by fish into nitrate. The outlet of the NFT pipes end into a sump where water is then poured back to the fish tanks after proper pH adjustments. This type of system offers the advantage that pipes can be moved and adjusted to increase/reduce the planting density according to the growth stage of the crop. In addition the lightweight is compatible for NFT to be developed on rooftops.

Although the system is very simple, it shows some drawbacks, which are found in the excessive daytime heating of the water flowing into pipes during the hot and in the vulnerability against black outs, as any lack of electricity immediately deplete the water into the pipes and stress/wilt, the plants. One solution to address the thermal excursions above mentioned, which also stress the animals, is to decouple the fish from the plant system in such a way that the two sub-systems could only communicate for limited period and for the strict time necessary to replenish nutrients into the plant sub-unit.

Fig. 7.19 NFT with round pipes positioned on A frames

Fig. 7.20 NFT with flat pipes

Advantages	Disadvantages
• Small flow of water, cost savings in pumping • Lightweight, suitable for roof-top agriculture • Suitable for both small or industrial scale farms • The concentration of nutrients can be adjusted real time (in hydroponics) to meet plant demand • High productivity if properly managed • Suitable for leaf vegetables, especially lettuces • Pipes can be moved to increase planting density • Suitable for water sterilization • Easy management • No media to handle	• Set up costs is high due to the number of pipes and supporting structures needed • The concentration of nutrients cannot be adjusted real time in aquaponics • Risks of black outs and loss of the whole production • Requires a biofilter and mechanical filtration • Extreme temperatures in water between night and day bring stress to the fish and make them sick • Higher risk of plant diseases with high water temperatures • Risk of lettuce bolt with high water temperatures

7.3.5.4 Media Beds

Media beds are very common in small backyard systems (Fig. 7.21). They are very versatile and can be used for both leaf, fruit and root vegetables. A whole range of inorganic media is used: expanded clay, tuff, pea gravel, and perlite.

Plants in such systems receive nutrients through surface irrigation by means of drippers or through flood-and-drain cycles. In flood-and-drain media is cyclically wetted by raising levels of water and then aerated when the water flows out from the tanks. Flood and drain can be operated by either the cyclical flushing of siphons that suck water out when water reaches a fixed height, or by the intermittent functioning of an inlet water pump given a constant, but smaller, outflow that allows the bed to be flooded. Media beds are very easy to manage, providing that fish wastewater is adequately clean from bulk solids to avoid organic matter build-ups and consequent anaerobic spots. This type of system is recommended for beginners who are neither experts in nitrification nor are constantly monitoring their systems. The presence of media helps the practitioners to have an adequate biofiltration and mineralization at the same time.

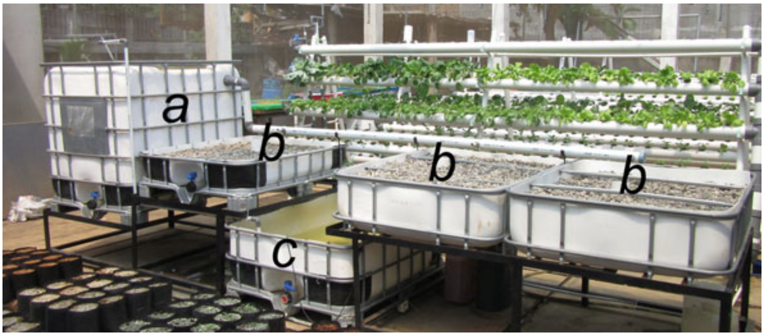

Fig. 7.21 Media bed obtained from IBC tanks: fish tank (*a*) with outlet serving the plant beds (*b*). Plant beds discharge water to the sump (*c*) where a submerged pump returns the water back to the fish

Advantages	Disadvantages
• Suitable for all types of plants (leaf, root, fruit) • Substrates used according to local availability • Carbonate-based substrates can buffer the water that tend to become acid with nitrification • Many water delivery options • Nitrification provided by media • Mineralization provided by media • Resilient to black outs	• Costs for transport of media • Not suitable for large scale farms • Heavy systems if using standard media (gravel) • Needs liners resistant to punctures

(continued)

(continued)

Advantages	Disadvantages
• Can be used for roof tops with lightweight media	• Media can clog with abundant fish solids • Plants can leave crop residues in the media • More labour during transplants • Media may damage stems in windy conditions • Water delivery may be not uniform, impair growth

7.3.5.5 Dutch Buckets

Dutch buckets are media-contained pots where plant grow by receiving the nutritive solution by means of drippers of by regular flood-drain cycles. This type of system is suitable for large fruiting plants or potted plants sold to the markets or to retailers. Being the plants growing in pots they can be easily moved to adjust the density according to their growth stage.

In aquaponics this type of systems has been developed with manifolds serving plants with adjustable flow of water, or by means of flood-drain cycles delivering water to plants positioned on a waterproof bed. The outflow from the pots directly converge to the fish tanks or to a sump. In general the pots with their media already provide biofiltration to the system water, but some degree of mechanical filtration is needed upstream, between the fish tanks and the pots, to avoid the accumulation of fish wastes and the clogging of the media. One positive aspect of this system is that irrigation by flood and drain does not require big investments. However, if the aquaponic water is delivered by micro-irrigation the delivery system may eventually clog due to the presence of organic matter and bacteria in the water that colonize the micro pipes. Should micro-irrigation be chosen a deep filtration with sand filter should then be guaranteed to get rid of all solids and secure a good quality water without any risk of clogging.

Advantages	Disadvantages
• Suitable for fruit plants and potted plants • Many water delivery options • Suitable for large-scale productions • Plant density adjustable • Nitrification/Mineralization provided by media • Resilient to temporary black outs	• Costs for transport of media • More labour for management • Needs liners resistant to puncture if pots are positioned above • Some water delivery options can clog (drip irrigation)

7.4 Aquaponics Versus Aquaculture Systems

At sustainability level aquaponics has the same advantages of any other aquaculture farming system. The production of fish brings in fact consistent advantages on water uses and ecological footprint, if compared to terrestrial animal husbandry. Being fishes cold blooded animals they do not consume most of the energy for heating their bodies, as it happens for mammals. This different physiology improves sensitively the fish efficiency in converting feed into body mass (feed conversion ratio—FCR). In fish FCR can be as low as 1 (1 kg of feed required to increase the animal body weight by 1 kg). On the contrary FCR values in chicken and mono-gastric warm-blooded animals are 3–4, while in ruminants they raise up to 6–7 (Verdegem et al. 2006). Low FCRs result in lower uses of land and water to produce the necessary feed for the livestock.

7.4.1 Traditional Systems

The evolution of traditional aquaculture to closed systems brought considerable advantages both in terms of pollution control and water use efficiency (Piedrahita 2003; Verdegem et al. 1999, 2006).

In many parts of the world aquaculture has not been managed with the necessary attention on environmental issues. Fish productivity strictly depends on the degree of farming intensification, which is a trade-off between land access, resource use (feed, energy, water) and waste production. In general traditional freshwater aquaculture is predominantly represented by pond systems.

The type of management intensification however affects the productivity of the aquaculture system, which varies accordingly to the use of inputs: *extensive* has no feed use but only fertilization is applied to increase the natural food production of ponds (phyto and zooplankton that is eaten by fish), *semi-intensive* with partial use of feed to integrate the natural pond productivity, *intensive* systems where feed fully covers the nutritional needs of the aquatic animals. Intensive systems make also use of energy to support the water oxygenation and water exchange to get rid of wastes and ammonia, which is toxic to fish (Barnabé 1990; Diana et al. 1997) (Table 7.6). However, new incoming water increases the risks of parasites and pathogens out-breaks, and put aquatic animals at risk of chemical contamination from outer waters, which makes it necessary to develop appropriate control strategies.

Table 7.6 Differences between aquaculture managements and productivity in tilapia growing in ponds (Diana et al., 1997)

	Extensive	Semi-intensive	Intensive
Fertilization	No fertilization or fertilization with manure or chemical fertilizers	Fertilization may be used	Fertilization may be used
Feed	No use of feed, fishes rely on pond natural food production	Partial use of feed to integrate natural pond food production	Complete use of feed to cover the nutritional needs of fish
Aeration	No aeration	No aeration	Aeration occurring
Water management	No water exchange	No water exchange	Water exchange in very intensive systems
Productivity per year	≤0.5 MT ha^{-1} with no fertilization; 1–3 MT ha^{-1} with fertilization	3–6 MT ha^{-1}	6–10 MT ha^{-1}; 10–20 MT ha^{-1} with water exchange

7.4.2 Advantages of Recirculating Systems

Closed recirculating systems have the considerable advantage that all the products from fish metabolism are processed within the system, although a certain amount of water is daily discarded to dilute the build-up of nutrients and to eliminate the bulk fraction of solids. However, this water exchange is minimal if compared against traditional aquaculture systems. In addition the small volumes of the incoming water is easily manageable through filtration and sterilization to control outer pathogens and parasites.

This closed management brings the overall water consumption per kilogram of fish produced to lower values (0.5–1.4 m^3) than traditional aquaculture, in which the overall water use depends on the management intensification: 4.7–7.8 m^3 for aerated ponds, up to 11.5 m^3 for extensive ponds, up to 30 m^3 for aerated pond with water exchange (Verdegem et al. 2006) (Table 7.8). In practical terms the very small volumes of incoming water required by closed systems can be easily and completely controlled and sterilized, bringing eventually to zero any risk to transmit diseases and pollutants into the systems.

RAS and aquaponic systems are a valuable method to grow fish in water scarcity conditions. The recirculation of water also limits the heat losses, which is beneficial in cold/hot climates as it saves major heating or cooling costs and maximize fish growth, since animals grow in optimal temperature ranges and optimal water quality.

7.4.3 Production and Quality in Recirculating Systems

In terms of performances the shift from traditional cage or pond culture to recirculating systems does not affect growth. In the case of tilapia FCR values from aquaponics range from 1.0–1.3 (Pantanella et al. 2012b) up to 1.7 (Rakocy, personal communication 2008) 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), is 0.91–5.1% in aquaponics (Seawright et al. 1998; Al-Hafedh et al. 2008, Pantanella et al. 2012b) versus 1.43–3.22% in earthen ponds, but under higher feeding regimes (Pruginin et al. 1988).

In the case of other warmwater species, such as young African catfish SGR from aquaponics (1.36–2.13%) (Endut et al. 2010; Pantanella et al. 2012b) is similar to recirculating systems (1.24–1.94%) (Pantazis and Neofitou 2003; Ahmad 2008). Likewise FCR in aquaponics (0.97–1.39) (Endut et al. 2010, Pantanella et al. 2012b) is similar to either earthen ponds (0.98–1.54) (De Graaf and Janssen 1996) and recirculating systems (0.94–1.29) (Degani et al. 1988). For some other species aquaponics has shown interesting growth rates and FCR, as shown in Table 7.7.

On a qualitative point of view RAS and aquaponics proved that the fish containment helps to prevent any risks of parasites or chemical/biological pollution from external water sources. On the other hand the rearing of fish in closed systems proved no risks of heavy metal build-ups in the flesh, if compared to the levels found in animals reared with traditional systems (Martins et al. 2011).

There is currently a wide debate about the genetic contamination of wild stocks with farmed fish, the difficulties in preventing the mutual transmission of parasites and pathogens between farmed and wild fish, and the raise in tolerance of parasites against common drugs. These issues are now bringing the industry and policy makers to consider different ways to produce. The farming of fish in closed systems could be undoubtedly a valid solution to address the environmental problems that are affecting the industry. However, given the higher investment costs the returns must be guaranteed by farming high-value fish.

In terms of costs both RAS and aquaponics require higher investments, but aquaponics gets some advantages for the slightly lower technology used and the conversion into profits of the water treatment costs normally occurring in RAS. In aquaponics the plant production part is eventually the main source of income for farmers, who may differentiate their output by combining animal with vegetable crops. However the combination of the two components may limit the management choices of either fish or plants, since the optimal environmental conditions of one can differ from those of the other crop.

Aquaponics, as well as recirculation, may not be convenient for farming fish that can be produced extensively or semi-intensively in ponds, as their selling prices barely cover the feed and energy costs occurring in closed systems. The higher investments and operating costs from intensive systems may not be covered unless

Table 7.7 Performances of fish species in aquaponics

Fish species	Stocking density (kg m^{-3})	Fish weight at stocking (g)	Feeding regime (% CP)	Diet (% BW)	FCR	SGR	Author
Bester sturgeon (*Acipenser ruthenus* × *Huso huso*)	7.56	95	46	2	1.01–1.25	1.38–1.66	Dediu et al. (2012)
Hybrid sex reversed tilapia (*O. mossambicus* × *O. niloticus*)	8.7	434	32	1.8–0.6	na	na	Mc Murty et al. (1997)
Sex reversed Nile tilapia (*O. niloticus*)	1.3–16	3.8	41.6	5.0–4.4	1.0–1.1	4.4–5.1	Seawright et al. (1998)
Sexed male Tilapia (*S. aurea*)	1.12	62	32	4.0–1.2	1.59	1.2	Watten and Buschs (1984)
Nile tilapia (*O. niloticus*)	4.86	32.4	41	0.6	na	0.8–1.1	Tyson et al. (2008)
Mixed sex blu tilapia (*S. aureus*)	1.68	na	na	na	1.32	na	Mc Murty et al. (1990)
Mixed sex Nile tilapia (*O. niloticus*)	6.8–39.7	42.5–248	34	3 to 2	1.0–1.7	0.7–1.8	Al-Hafedh et al. (2008)
Nile tilapia (*O. niloticus*) (1) Red tilapia (*Oreochromis* sp.) (2)	5.4 (1) 10.8 (2)	70	32	ad libitum	1.79	na	Rakocy et al. (2004a)
Nile tilapia (*O. niloticus*) (1) Red tilapia (*Oreochromis* sp.) (2)	6.1 (1) 9.1 (2)	79.2 (1) 58.8 (2)	32	ad libitum	1.7 (1) 1.8 (2)	1.39 (1) 1.29 (2)	Rakocy et al. (2004b)
Mixed sex Nile tilapia (*O. niloticus*)	8 (1) 20 (2)	24 (1) 90 (2)	43 (1) 40 (2)	2 (1) 1.7 (2)	1.0 (1) 1.3 (2)	2.7 (1) 1.4 (2)	Pantanella et al. (2010)
Nile tilapia (O. niloticus)	10.7	100	na	2.5–1.25	na	na	Savidov (2005)
Red tilapia (*Oreochromis* sp.)	7.1–8.8	38.9	32	6–1.2	1.76	na	Rakocy et al. (1997)
GM Nile tilapia (O. niloticus)	15	10	40	2.5–1.1	1.57–3.9	4.2–0.08	Pantanella et al. (2011c)
Tilapia (*T. mossambica*) (T) & common carp (*Cyprinus carpio*) (C)	40	na	na	5		3.14 (T) 2.56 (C)	Naegel (1977)

(continued)

Table 7.7 (continued)

Fish species	Stocking density (kg m^{-3})	Fish weight at stocking (g)	Feeding regime (% CP)	Diet (% BW)	FCR	SGR	Author
African catfish (*Clarias gariepinus*)	9 (1) 21 (2)	81 (1) 183–193 (2)	31–40	2 (1) 1.5 (2)	0.97–1.1 (1) 1.25–1.3 (2)	2.0–2.1 (1) 1.36 (2)	Pantanella et al. (2011a, b, c,d)
African catfish (*Clarias gariepinus*)	na	30–40	32	2–4	1.23–1.39	1.68–1.83	Endut et al. (2010)
Murray cod (*Maccullochella peelii peelii*)	10	120–220	43	1.0–1.5	0.8–1.1	0.9–1.1	Lennard and Leonard (2006)
Mullet (*Mugil cephalus*)	7.4–8.1	83.2 (1) 84.9 (2) 100.4 (3)	54	0.5–0.6	3.5–4.5 (1) 2–2.2 (2) 3.1–3.2 (3)	0.1–0.2 (1) 0.4–0.5 (2) 0.25 (3)	Pantanella et al. (2011b)
Largemouth bass (*Micropterus salmoides*)	11	33.6	44	0.9	1.5	0.77	Pantanella, unpublished data

%CP percentage of crude protein, *%BW* percentage of body weight, *FCR* feed conversion ratio, *SGR* specific growth rate

Table 7.8 Comparative advantages and disadvantages, water use and productivity of aquaponics and RAS against traditional aquaculture (Verdegem et al. 2006—modified)

	Semi intensive ponds	Intensive aerated pond	Intensive aerated pond and water exchange	Aquaponics, RAS
Advantages	– Easy management – Low investments – Natural feed and pellet – Low production costs of fish – Integrated aquaculture	– Relatively low management – Pellet as main feed source, but natural feed still plays a role – Control on aeration	– Higher yielding – Control on aeration – Water monitoring – Ammonia monitoring – Use of pelleted feed	– Small land footprint – High environmental and water control (indoor) – High productivity – Safety (indoor) – Low need of water – Farming everywhere
Disadvantages	– Land demanding – Consistently rely on water sources – Contaminant risk – Disease risk (outdoor)	– Rely on feed – Rely on energy – Sludge accumulation – Limited choices to raise density – Contaminant risk – Disease risk (outdoor)	– Rely mainly on feed – Energy intensive – Rely on water – Sludge accumulation – Pollution of water (water discharge) – Contaminant risk – Disease risk (outdoor)	– Rely only on feed – Energy intensive – Management intensive – Multiple skills – Higher risk of failure for any breakdown – High investments – High running costs
Productivity (MT ha^{-1} y^{-1})	2–8	4–20	15–35	>100
Water use (m^3 kg $fish^{-1}$)	11.5	4.7–7.8	30	0.15–3.2

valued fish are cultured or commercial species are sold in markets where premium prices are applied for quality fish sold with no residues and pollution issues.

Aquaponics can be a valuable option in fish nursery productions, as the high turnover of the fry, the high stocking densities achievable and the higher degree of biosecurity guarantee for good incomes and reduced losses than traditional pond management.

A comparison of advantages and disadvantages of aquaponics/RAS against traditional systems outlines the small footprint and higher productivity of such advanced systems (Table 7.8), however the final decision for their use depends on the degree of risk that the fish farmers are willing to take.

7.5 Aquaponics Versus Agriculture Systems

7.5.1 Advantages of Soilless Systems Against Traditional Agriculture

Aquaponics and hydroponics overcome some of the problems commonly occurring in soil-based agriculture, which have been increased by the adoption of monoculture practices in greenhouses (Table 7.9). Typically with soil-based agriculture farmers have to carry out a series of tasks to prepare and manage their crops, which imply ploughing, removal of weeds and fertilization, irrigation, weed control. In addition agriculture farmers do not have control on the release of nutrients from soil, which is affected by the soil texture, its chemical characteristics in binding nutrients (cation exchange capacity), and environmental conditions (temperature). At the same time farmers have limited strategies to cope with salinity.

In terms of productivity soilless cultivation increases the crops' water use efficiency up to ten times, while the crop productivity can be more than doubled than conventional agriculture (Resh 2004).

Soilless cultivation can be developed in urban and suburban areas, which sensibly reduces transport costs. Furthermore aquaponics can be developed in areas not suitable for traditional agriculture due to exhaust soil conditions or bad water quality. Aquaponics fits particularly well the needs to produce food wherever there is no fertile land or access to land, but in terms of economic competitiveness the adoption of aquaponics in fertile areas has to be carefully assessed due to the higher investment and production costs than traditional agriculture.

To summarize soilless systems show some advantages over conventional soil-based systems:

- Increased yields due to cultivation in protected environments, in which it is easier to control the climatic parameters optimal for plants
- Lack of competition for nutrients from weeds
- Control of nutrients according to the growth stage and nutrient requirements of the crops

- Increase in quality of productions, due to optimal plant nutrient balances
- Reduction in residues and pesticide due to integrated/biologic management
- Better organoleptic and nutraceutical characteristics due to optimal nutrient management
- Lack of crop rotation to avoid "soil tiredness" that reduce crop yields over the years
- Better control of soil-borne diseases through physical avoidance of micro-organisms and biological management.

7.5.2 Differences Between Aquaponics and Hydroponics

Aquaponics differs from hydroponics. Although similar management can be applied in both systems, aquaponics is a more complex agroecosystem in which the presence of both fish and micro-organisms play a key role in plant Growth (Table 7.9). In aquaponics the levels of nutrients are lower than hydroponics, and most of the times the level of nitrogen used is 20–40% of the concentrations normally in use in hydroponics. The reason of such productivity in lieu of low concentrations of nutrients stands in a constant, but continuous, supply of micro and macro elements by fish. Nevertheless the more complex dynamics in aquaponics allow plants to uptake also free amino acids from water and fulfil equally their nutritional purposes (Ghosh and Burris 1950).

The presence of microorganisms in the water lead to a different management of aquaponics systems. Contrarily to hydroponics, which is mainly kept sterile to avoid pathogens' contamination, in aquaponics the complex habitat created by beneficial bacteria and fungi makes the system less prone to diseases, due to the high competitive environment the pathogens have to face.

The system complexity however raises the need to have higher levels of knowledge and expertise from operators, who should be aware of the different needs of both plants, fish and bacteria/fungi. The integration of these three living elements raises the need to get some compromises in either water (pH, temperatures, nutrient levels) and ambient/climate management.

One drawback of aquaponics, however, is found in the need to combine two different management at one time, which results in suboptimal conditions for either fish or plants. If the presence of the aquatic animals from one side testimonies for the safety of the products, on the other hand it severely limits the choices for disease and pest management. Many of the remedies in use in organic agriculture could not be applied to plants due to toxicity for fish, and have to be refrained unless they are used under strict control in limited cases. The aquaponic ecosystem is manageable providing that a bunch of preventive remedies are put into action to avoid any spread of pests or diseases into the system. Therefore preventive management requires high expertise in people who should know the dynamics of fish and plants, as well as be aware of epidemiologic factors.

Table 7.9 Comparative advantages and disadvantages of aquaponics against traditional hydroponics and soil cultivation

	Aquaponics	Hydroponics	Soil
Flexibility to new areas/climates	Possible. But needs to consider fish requirements	Possible. Agriculture even in extreme conditions (desert)	Not possible if soil is not fertile
System control	More complex, need also to consider animal optimum	Adapted to the crop (greenhouse)	Adapted to the crop (greenhouse)
Ambient conditions	Can be affected by higher humidity due to fish tanks	Standards of protected controlled agriculture (greenhouse)	Standards of protected controlled agriculture (greenhouse)
Water use	Low, as it compensates only for evapotranspiration and evaporation	Very low, as it compensates only for plant evapotranspiration	Medium, high. Depends on the delivery system and soil characteristics
Water physical characteristics	Should compromise plants and fish needs for either pH, temperatures	Optimal for plants	No water control
Nutrient concentrations	Can be low, due to constant fish supply	High	Medium to high. Release of nutrients affected by soil and weather/climate, leaching
Nutrient use efficiency	High, similar or better nutrient use efficiency than hydroponics due to lower concentrations of nutrients in the solution	High, minimal amount of fertilizers used, uniform distribution and real time adjustable flow of nutrients. No leaching-dispersal	Low, affected by soil, leaching and weather/climate
Use of space	Optimal, at least twice as productive as soil	Optimal, at least twice as productive as soil	Medium, depends on soil fertility
Soil-borne disease and pests	Not affected	Not affected	Affected
Epidemiology	Minimal risk of soil borne diseases, due to system resiliency. Higher risk of leaf diseases (fungi) due to higher humidity from fish tanks	Risk of disease spread higher due to use of same aqueous media to all plants (closed system)	Risk of disease spread higher due to runoff of contaminated water

(continued)

Table 7.9 (continued)

	Aquaponics	Hydroponics	Soil
Sanitation	Risk of contamination due to use of water with coliforms from fish. Sterilization of water is possible. No *E. coli* risks because fish are cold blooded animals	No risk of contamination for human health	Risk of contamination if using water from canals
System management	Organic-like but not certifiable organic (in EU)	Chemical or integrated	Chemical, integrated, organic
Product quality	Similar or higher to hydroponics. Higher presence of metabolic compounds may benefit	Full control with appropriate nutrient delivery and adjustable nutrients and salinity at fruiting stage	Variable, depends on the soil and management. Fruits may be better tasting
Investment costs	Higher than hydroponics due to the need to set up the fish system as well	High, due to setting up of protected environment, nutrient delivery and monitoring	Low, but needs investments on machineries
Management	Highly expert knowledge needed, due to fish/plant presence	Expert level is needed to cope with instruments and settings	Medium level
Risk	High risk of failure if electricity is down with no backup system	Medium, depends on automation	Medium, more affected by environmental conditions

In terms of productivity the scientific literature has already proven that aquaponics is as efficient as hydroponics both in terms of yields and quality, providing that certain nutrient ratios are maintained. In terms of market aquaponics has a better outlook than hydroponics for its organic-like management. In USA aquaponics can benefit from organic certification, which opens up produce to premium price markets. On the contrary EU regulations limit organic productions to soil-based agriculture despite the biological outlook of aquaponics and its full cycling of nutrients. Nevertheless the expansion of aquaponics is still limited due to higher investment costs than hydroponics that prevent farmers from considering this technique a much profitable alternative.

Aquaponics could experience good growth if it is developed as decoupled system, in which one farmer specializes in fish production while the another gets the aquaculture wastewater for plant production. The separation of the two subunits increases the opportunities to improve both pest and disease management, since there is no cross-contamination between the subsystems.

7.6 Production Systems in Use

7.6.1 Commercial Productions

A recent survey on commercial scale producers (Love et al. 2015) traced the identikit of the average aquaponic farmer. The majority of commercial farms are based in the USA with the owner having a leading role in the venture for at least 49% of the cases. Most of the commercial farms produce on DWC (77%) and media beds (76%), the data also testimony that a combination of different systems is the norm. The average farms are not big: size of 100 m^2, investment of 5000–10,000 USD, no cold storage room at least for half of them and no food safety plan for 38% of them. Aquaponic farms appear more vegetable-oriented rather than fish-oriented due to the length of the fish crops, though 69% of farms reared tilapia, a fish that can be harvested up to commercial size in only six months. The prevalence of leafy greens and herbs witnesses the orientation of farmers to high-return crops.

There is a big interest worldwide in adopting aquaponics for commercial horticulture. On this point research and pilot scale projects (Fig. 7.22) at different latitudes are focusing at demonstrating the economic feasibility of integrated systems and at optimizing their sub-components. There are ongoing collaborations between research institutions and the industry. A European Cooperation in Science and Technology—COST program FA1305 started in 2014 gathering research institutes and private companies with the scope to organize a comprehensive aquaponics platform for research and commercial development. Likewise in North and South America universities are partnering and fostering research and development for the support of the aquaponics sector.

Fig. 7.22 A pilot scale system in Europe

Big farms are increasing in number especially in North America. In Canada many firms are extensively producing aquaponics lettuces with DWC often using a degree of mechanization in harvest. In USA the leading design is the UVI system, with many farms replicating the ratios and the components. The success in North America is also driven by the possibility to certify organic the produce, which brings high revenues and good returns on investments. In Europe there is an expansion of aquaponic farms especially in the northern countries. The success stands in the green outlook of the technology and the awareness of consumers for safe products. Aquaponics has however good potential for expansion in water scarce countries. In the Middle East many countries are strategically planning production systems with water saving technologies as a way to guarantee their food security and to make the countries as much self-sufficient as possible. In UAE at the Zayed Agricultural Centre, an UVI type system of nearly 2000 m^2 of cultivable area, was built to show the potential for integration of fish and plants. Currently across the whole region private entrepreneurs and trusts are planning to build aquaponic systems for commercial operations following their respective country directives for food security, water security and self-sufficiency.

7.6.2 *Small Scale for Backyard Consumption, Market and Food Security*

Most of the small scale systems are meant for home consumption. Although not directly involved in commercial scale operations these systems proved to be supportive for family needs either for the supplement of chemical-free vegetables or to reduce the family retail expenditures at the grocery. According to a survey carried out in 2013 (Love et al. 2014) the average size of backyard farms are 15 m^2 with vegetables playing the main role. Interestingly most of the farmers do aquaponics more as a hobby and the main drivers in the production are sustainability and the production of own (safe) food. Aquaponics is growing mostly in urban and peri-urban areas due to the fact that micro scale agriculture is either considered a

Fig. 7.23 Micro scale system

leisure and because of the characteristic of soilless production: intensive outputs within small acreages wherever fertile land or other inputs are scarce (Fig. 7.23).

Aquaponics is also considered a strategy for food security not only because of the production per se, but because of the cash derived from selling small amounts of vegetables in local markets. In recent years FAO, the Food and Agriculture Organization of the United Nations, implemented microscale aquaponics projects for food security in the Middle East and Africa and showed that household food production is improved, can empower women and be more sustainable and resilient whenever production is organized at community level throughout the whole production chain (from seed to market) and under the credit support of revolving funds. Recent FAO workshops also witnessed the growing interest in promoting aquaponics as a water-saving food production technology to be used on islands or in conditions of scarce water resources, which is particularly important in many climate-change affected areas.

Advantages	Weaknesses
• High productivity with limited spaces • Landless food production • Seasonal-free productions in protected environments • Valorisation of household work • Women empowerment • Improved access to the markets • Improved value of products • Improvement of household food security • Household cash for health and education	• Higher initial investment costs than other traditional but low yielding systems • Higher degree of skills needed for the management of both plants and fishes • Grow out systems, need to rely on constant supply of inputs and fingerlings • Electricity not reliable in some areas • Need to produce high quality and high value crops and fish to be highly profitable • Market access to be developed

7.7 Alternative System Designs

Aquaponics combines fish and plant species within the same environment. This integration includes also beneficial bacteria involved in the nitrification, which work in optimal ranges of pH, temperature. Most species are adaptable to variable conditions, but not always it is possible to let each crop to grow under optimal environmental parameters. One of the main aspects that additionally limit the choices of the management in aquaponics is the risk of cross-toxicity in using any biological remedies for pest control, which results in some cases in crop failures or fish losses. In recent years there has been a constant and growing interest in separate the fish and plant units to ease the management through decoupled or hybrid systems.

7.7.1 Decoupled Aquaponics Systems

The rationale of these systems is that both fish and plants live in separate environments that are temporarily connected just to bring nutrients from fish to plants or reclaimed water back to fish. Basically a decoupled system is the combination of a RAS and a hydroponic unit using fish wastewater as source of nutrients. In terms of management such solution ease the farming of fish that are always reared in optimal conditions of temperatures and water parameters. On the other hand the standalone plant growing areas are set with optimal pH, humidity and temperatures set for the vegetable crops. The decoupled aquaponics systems can be managed with periodical recirculation of water between the fish and plant subsystem (two-way, or hybrid system) (Fig. 7.24) or can be run in unidirectional way with water going

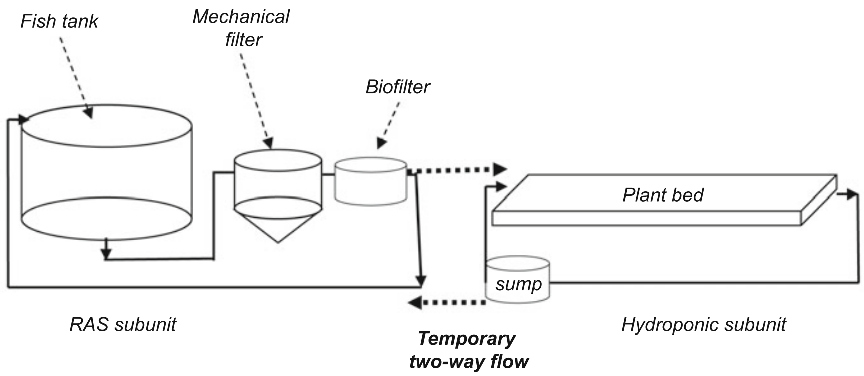

Fig. 7.24 A two-way decoupled system (hybrid RAS). The RAS and hydroponic subunits work as standalone units but are temporary connected to allow nutrient-rich water to go to the plant bed and reclaimed water from the plant to the fish subsystem. The plant bed still works as a biofilter and supports the nitrification needs of the fish subunit

only from the fish to the plant subsystem (one-way system) (Fig. 7.25). In terms of practical management this second option is seen more favourably by plant growers, who do not have to be worried about any risk of toxicity to fish. Such type of open system well suits the needs of outdoor agriculture with ferti-irrigation lines serving rows of plants.

One of the advantages of decoupled systems is that they do not necessarily need experts in both fish and plants, as one farmer just specializes in recirculating aquaculture, while another one specializes in soilless cultivation by using fertilized water from the fish producing neighbour.

In terms of investment this solution would ease the adoption of aquaponics, as farmers would not necessarily need to double the investment on both fish and plants, but can outsource one of the two while concentrating in their main and single core business.

7.7.2 Low-Tech Designs

At backyard level there is interest in developing low-tech systems that are simple and of immediate understanding by farmers. The Indonesian *Yumina-Bumina*, for example, re-thinks at aquaponics in a very simple and comprehensible way for whoever is used to pond culture. Surrounding pots all-around the banks or walls of the tank help the water quality to be maintained at optimal levels while delivering fertilized water to the plants (Figs. 7.26 and 7.27). The media contained in the pots procure at the same time solid entrapment, biofiltration and mineralization of the fish water. Yumina-Bumina uses higher fish stocking densities than traditional aquaponics, also because the size of the harvested fish is rather small and targets the single person portion sizes. The Yumina-Bumina stocks fingerlings of catfish at 300–500 fish m^{-3}, 50 fish m^{-3} for Nile tilapia.

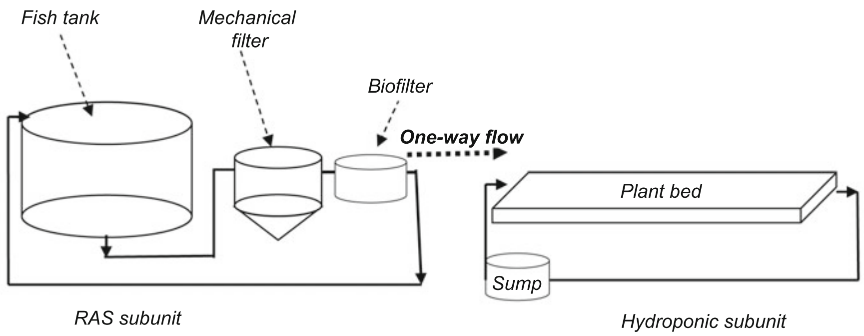

Fig. 7.25 A one-way decoupled system. The RAS and hydroponic subunits work independently. The plant bed receives the fertilized water from the fish subunit. This system allow farmers to have more freedom in their integrated pest/disease management

Fig. 7.26 A yumina-bumina system with pots

Fig. 7.27 A floating yumina system

In general such systems use a fish pond:plant ratio of 0.25 m^3 m^{-2}, which means that every cubic meter of pond water corresponds to 0.25 m^2 of plant growing area. The production cycle is quite fast as the harvest in catfish occurs in only 2–2.5 months, while gourami and pangasius in 6–12 months. For tilapia the harvest of mix-sex fish occurs before they reach sexual maturity at the age of 4–5 months, which completely bypasses the need to carry out sex reversal in these fish.

The focus on low-tech systems is important in emerging countries where the limited access to money for investment and the lack of knowledge of the dynamics of aquaponics prevent many from adopting backyard systems. Nevertheless systems that approach the traditional way agriculture is managed and that require low maintenance are ideal to meet the limited skills of local households. In Myanmar a demonstration facility with a tank serving a gravel bed proved that a 30 m^2 system that includes a bamboo nethouse and a solar system for standalone energy supply would cost as low as 25 USD m^{-2} and bring a net profit of 1.6–2.2 USD a day from vegetables and secures a fish consumption of 400 grams per day (Pantanella et al. 2014). Similarly Dr. Wilson Lennard from his researches could produce aquaponic kits for backyard farming in developing countries serving a few square meters of plant beds for as less as 100 USD.

The aquaponics concept could be applied to staples or even to traditional agriculture. The key factor stands in the recirculation of the water that allows for the build-up of nutrients to levels that guarantee for commercial productions of crops without any addition of chemical fertilization. Some experiments carried out with tilapia and rice growing on sand beds proved higher rice yields than chemically fertilized paddies (respectively 8.1 and 5.1 MT ha^{-1}) in 120-day crops with a fish:plant ratio of 1–1.5 kg. Interestingly, considering the short duration of fast growing varieties of rice, it would be possible to perpetually support the daily rice needs of a family of 5 members with only 100 m^2 of growing area (Pantanella et al. 2011c).

7.8 Saline Aquaponics

Saline water provides new opportunities to farm fish and plants in a more sustainable way. Despite its wide diffusion cage farming has never obtained a full acknowledgement due to pollution issues, the risk of genetic contamination of wild stocks due to escapees and disease outbreaks, the competition with other water uses for recreational purposes. In the last decades the integrated multi-trophic aquaculture (IMTA) provided some solutions to the control of the pollution from fish cages, but it has obtained limited impact due to the high water dilution of nutrients in open bodies.

Aquaponics with its build-up in nutrients provides opportunities for marine and brackishwater aquaculture to control the potential source of pollution by preventing organic wastes to be released into the environment and to obtain at the same time additional incomes from plant production. Turning fishes out from cages into recirculating systems not only does maintain the optimal growth parameters of fish, but would also achieve higher levels of biosecurity against pollutant and pathogens, which eventually guarantee for higher yields and safer aquaculture productions.

Saline aquaponics does not differ much from the freshwater aquaponics, with the only exceptions that biofiltration has to be scaled up to compensate for the lower nitrification efficiency of bacteria under higher salinity, and the need to increase the concentrations of nutrients to compensate for the reduced plant uptake due to higher osmotic pressure in the water.

The salinity level in water definitely affects the type of system in use and the fish and plants choice. Some marine species such as European seabass (*Dicentrarchus labrax*) and seabream (*Sparus aurata*) respectively grow well at salinity of 5–7 g L^{-1} and 10 g L^{-1}, while mullet (*Mugil* spp.) and Asian seabass (*Lates calcarifer*) can reach nearly freshwater conditions.

The decrease in salinity, within certain physiological limits, rather than being a depressing factor can improve the growth performances of fish, which do no spend energy for balancing the osmotic pressure of highly saline water.

Fig. 7.28 Basil growing at 3 g L^{-1} salinity can achieve similar yields per m^2 of plants growing on freshwater hydroponics by simply improving density, climatic control and use of anti stress factors

Although salt is not the best element for plant growth due to the toxicity of sodium and the reduced capacity of plants to uptake water against a negative osmotic pressure, it is possible to crop some traditional horticultural plants that show a degree or resistance at salinity levels of 0.5–7 g L^{-1}. In addition, tailored agronomic strategies such as reduction of water stress conditions, improved fertilization, the grafting of commercial varieties on salt-resistant rootstocks, the use of anti-stress factors can greatly help to increase productivity up to the yields achievable in freshwater hydroponics (Fig. 7.28).

Besides, salt-tolerant plants (halophytes) can tolerate concentrations up to marine strength and show interesting commercial opportunities for leaf productions. The most known are *Salsola* spp. (Fig. 7.29), *Atriplex* spp, *Kochia scoparia*, sea fennel, *Salicornia* spp, seabeet (Fig. 7.30). There are also at least fifty different species of grain crops that can be simply cultivated with irrigation lines in outdoor conditions. There is also growing interest in seaweed for their nutritional and nutraceutical characteristics. They can be cultivated in closed systems and can

Fig. 7.29 Salsola optimally grows within 10–20 g L^{-1} salinity

Fig. 7.30 Seabeet growing at 10 g L^{-1} salinity on DRFT

greatly benefit from nutrients released by fish. Closed conditions also secure controlled production standards and compliance to food safety regulations.

The type of farmed aquatic animal strictly affects the choice of plants or seaweeds that can be cultivated based on the salinity ranges. In the case of saline aquaponics it is thus important to develop preliminary market studies to assess the demand of crops, the margin of profitability and the risk factors to secure economical sustainability of the ventures. Besides, the development of systems with cost-effective designs and technologies are the safest strategy to guarantee quick returns on investments.

7.9 Future Research

Most of the research on aquaponics has been carried out on the nutrient balances between different species of fish and plants. Contrarily to the past, when the focus was more on the engineering aspect of the system there is nowadays raising interest to determine the quality of the productions and to develop effective growth strategies. There is indeed a great deal of research topics that need to be explored, most of them pertaining the optimal nutrition of plants and the ways to modulate the concentrations of nutrients according to the growth stage of the plants. Secondly, research is also targeting new designs that can best meet the crop needs and be energy-saving.

Since 2014 the European funded EU COST FA1305 action has gathered the academic, research and development sectors with the SMEs from many European and no EU countries to evaluate the state of the art of aquaponics and to join the efforts in innovation and education. The action of research and development is mainly oriented towards the water quality management, the alternative sources of feed for aquatic animals, the best combinations of fish and plants in different latitudes also in a perspective of food security, in the assessment of the economic feasibility of aquaponics against other alternatives, and in the review of indicators for ecological, social and economic sustainability.

The assessment of the economic feasibility and the research of alternative system designs that best suit the need of the industry and small farmers is at the top of the agenda of many researchers and stakeholders. Recent aquaponic workshops carried out by FAO have arisen the need to develop clear assessment of the costs and benefits of aquaponics to let farmers and entrepreneurs be informed of the advantages/disadvantages of adopting this integrated system under their respective climatic and environmental conditions.

The engineering research is currently looking at alternative ways of running aquaponics from recirculating systems. On this large interest is now put in decoupled aquaponics, where the fish and plants subunits are managed separately, but temporarily communicate for the delivery of nutrients or for the return of reclaimed water back to the fish. Therefore there is the need to optimize the fish sub-units to let them reach good balances of nutrients for plants to be grown in similar conditions of traditional hydroponics.

The idea to make the aquaponics systems as much self-reliant as possible is another key research topic. In Canada the research team lead by Dr. Nick Savidov is working on the 5th generation aquaponics with the aims to produce zero-waste through complete mineralization of fish solids. On the other hand a team of researchers in Europe are focusing on the internal production of supplementary food to reduce the costs from feeds.

In developing countries the focus is on building systems suitable for the spending capacity of the locals and are of adequate simplicity to be used by low-educated farmers with hassle-free management and with low energy demand. Besides, there is the need to widen the potential of aquaponics to grow staple crops, which can guarantee for food security in areas where traditional agriculture cannot be done for either natural or anthropic causes. All these research solutions however need to be assessed against the costs and the economic advantages they can bring to the production system to make them really sustainable and adoptable.

7.10 Concluding Remarks

Aquaponics is a valid production system that meets the need to produce more with less inputs. The research in the past years has proven that systems are robust to handle both fish and plants and the productive traits of the crops are competitive against soil-based agriculture and hydroponics, even with lower levels of nutrients.

Aquaponics well suits the need of the fish industry for more sustainable productions, as it consumes less water and reduces down to zero the impact of wastes on the environment by re-using them in substitution of chemical fertilizers. The use of water in aquaponics is the lowest in aquaculture and comparable to advanced RAS without the hassle of more sophisticated and expensive technologies for water treatments. Aquaponics also complies with the need for high quality food, as its closed recirculating system reduces any risks of contamination with outer pollutants and prevents the contact with pathogen and parasites from unprocessed water, which eventually offsets any use of drugs.

There is however a number of areas of research that still need to be addressed to fully improve aquaponics to be adopted at industrial scale. This include the choice of plants to best meet each environmental condition, the climatic control of aquaponics, the decoupled technology for easier management of plant-only or fish-only systems, and the food safety issues for the retail sector. Also one of the key requirements for the expansion of aquaponics is the validation of its cost effectiveness.

Integrated systems have a great potential to improve agroecosystems efficiency. Nevertheless performances and economic sustainability are always factors influenced by environmental conditions, sub-system design and management. Increased productivity and sustainability of agroecosystems should further consider the optimal management of input, output and by-product as an important factor to improve overall system efficiency.

The system integration is the key factor for low input productions. However, the complexity of agroecosystems due to fish and plant integration requires increased management and environmental needs of plants, animals and their surrounding habitat. Aquaponics is as efficient as hydroponics in producing high quality food. However the full expansion of every integrated system would be only possible when products have lower production costs than traditional agriculture, or when aquaponics brings higher and faster returns on investments than hydroponics or traditional aquaculture. The key for the long term success of aquaponics would eventually be the perfect trade-off among environmental, social and economic sustainability.

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