Hydroponic systems and water management in aquaponics: A review

Carmelo Maucieri,1,2 Carlo Nicoletto,1 Ranka Junge,2 Zala Schmautz,2 Paolo Sambo,1 Maurizio Borin1

1Department of Agronomy, Food, Natural Resources, Animals and Environment, University of Padova, Legnaro (PD), Italy; 2Institute of Natural Resource Sciences, Centre Ecological Engineering, Zurich University of Applied Sciences, Wädenswil, Switzerland

Abstract

Aquaponics (AP), the integrated multi-trophic fish and plants production in quasi-closed recirculating system, is one of the newest sustainable food production systems. The hydroponic component of the AP directly influences water quality (in turn influencing fish growth and health), and water consumption (through evapotranspiration) of the entire system. In order to assess the role of the design and the management of the hydroponic component on the overall performance, and water consumption of the aquaponics, 122 papers published from 1979 to 2017 were reviewed. Although no unequivocal results were found, the nutrient film technique appears in several aspects less efficient than medium-based or floating raft hydroponics. The best system performance in terms of fish and plant growth, and the highest nutrient removal from water was achieved at water flow between 0.8 L min⁻¹ and 8.0 L min⁻¹. Data on water consumption of aquaponics are scarce, and no correlation between the ratio of hydroponic unit surface/fish tank volume and the system water loss was found. However, daily water loss was positively correlated with the hydroponic surface/fish tank volume ratio if the same experimental conditions and/or systems were compared. The plant species grown in hydroponics influenced the daily water loss in aquaponics, whereas no effect was exerted by the water flow (recirculating flow/drain cycle or constant flow) or type (medium-based, floating or nutrient film technique) of hydroponics.

Introduction

Aquaponics (AP), the combination of hydroponics and recirculating aquaculture (Rakocy et al., 2003) is a promising solution for the negative environmental impacts typically associated with intensive fish and crop production. In these integrated systems, nutrients that are excreted by the fish or generated by microbial activity (Munguia-Fragozo et al., 2015; Zou et al., 2016a) are absorbed by hydroponically cultured plants, thus treating the water before it is recycled to the fish tank (Endut et al., 2009; Tyson et al., 2011; Nichols and Savidov, 2012; Medina et al., 2016; Nuwansi et al., 2016). AP has received considerable attention due to its capability to sustain water quality, minimise fresh water consumption, and provide a marketable vegetable crop (McMurtry et al., 1997a, 1997b; Adler et al., 2000a; Lennard and Leonard, 2005; Graber and Junge, 2009; Danaher et al., 2011, 2013; Pantanella et al., 2011, 2015; Espinosa Moya et al., 2016; Shete et al., 2016). Nevertheless few microbial studies have been conducted to determine food safety status (Elumalai et al., 2017) suggesting that further research is needed to evaluate this aspect.

In the AP, the water quality required for fish production is maintained through biofilter and/or hydroponic section where: i) plants absorb dissolved fish wastes and products of microbial activity (McMurtry et al., 1993; Danaher et al., 2013; Silva et al., 2015; Goddek et al., 2016; Andriani et al., 2017); ii) several substances are removed through gas volatilisation (CO₂, CH₄, N₂, N₂O, NH₃, etc.) by the same processes as in constructed wetlands (Mander et al., 2014; Maucieri et al., 2017).

Due to its integrative character and multiple application scenarios from high-tech to low-tech, AP is an atypical and complex food production technology (König et al., 2016). As reviewed in Goddek et al. (2015), AP can be considered a sustainable agricultural production system and, in this respect, Lehman et al. (1993) define sustainable agriculture as agricultural practices which do not undermine our future capacity to engage in agriculture. Furthermore, Francis et al. (2003) report that production process inefficiencies can be reduced designing systems that close nutrient cycles, which is one of the main aspects of aquaponics (Goddek et al., 2015). However, daily water loss was positively correlated with the hydroponic surface/fish tank volume ratio if the same experimental conditions and/or systems were compared. The plant species grown in hydroponics influenced the daily water loss in aquaponics, whereas no effect was exerted by the water flow (recirculating flow/drain cycle or constant flow) or type (medium-based, floating or nutrient film technique) of hydroponics.
The essential components of an aquaponic system are the fish-rearing tank, the settler, the biofilter and the hydroponic unit (Rakocy et al., 2012). As AP is a recirculation system, each component influences the entire process. The hydroponic component directly influences water quality, which is essential for fish rearing (Yildiz et al., 2017). It is also the main source of water loss by plant evapotranspiration. Because the design and operation of the hydroponic system influences the sustainability of the entire process, either directly in terms of water consumption and/or indirectly in terms of system management costs, particular attention should be paid to it. In order to contribute to the discussion on the importance of the hydroponic unit, we reviewed 122 papers published from 1979 to 2017 to summarise the effects of the hydroponic system type, and of the water flow on aquaponic systems performance and water consumption.

Hydroponic systems

Current hydroponic cultivation systems can be classified in relation to the method of nutrient solution supply to the plant roots (Hussain et al., 2014a). They can be also classified in two major groups: i) cultivation systems without substrate that include the nutrient film technique (NFT) (Cooper, 1979) and different types of floating raft systems; ii) medium based systems, where a certain volume of substrate ensures roots anchorage, and acts as substrate for microorganisms’ attachment and water-nutritional flywheel (Figure 1). These last systems can be further distinguished on the basis of substrate used: organic, inorganic and synthetic (Enzo et al., 2001).

The choice of hydroponic type for an AP system may be based on the independent advantages conferred by any particular hydroponic component (Lennard and Leonard, 2006) or on life cycle assessment impact (Forchino et al., 2017). All the methods represented in Figure 1 can be integrated in an aquaponic system (Patillo, 2017). However, choice influences the design of the entire system. For example, the need to install a separate biofilter depends on the hydroponic system type. In media-based hydroponic systems, the used medium usually provides enough surface for bacteria growth and filtration although mechanical filtration between fish and hydroponic components can be useful to maximise biofiltration performance. Conversely, NFT channels do not provide enough surface for bacteria growth and additional biofilters have to be installed (Nelson, 2008). An overview of hydroponic systems implemented in aquaponics studies from 1993 to 2017 is provided in Appendix. Most of these publications refer to a single hydroponic system and the most frequently used systems were the medium-filled growth beds followed by floating rafts (Figure 2). Only one species was cultivated in the majority of experiments (Figure 3). The medium-based hydroponics is also the system where the highest number of species has been tested, followed by floating rafts and NFT; lettuce (Lactuca sativa), water spinach (Ipomea aquatica), and tomato (Lycopersicum esculentum) were the most frequently used species (Figure 4).

Only 9% of the reviewed publications compared different types of hydroponic systems (Figure 2). Lennard and Leonard (2006) evaluated the effect of hydroponic system type (gravel bed, floating or NFT) on nutrient stripping, plant yields and fish growth in a 21-day experiment with Murray cod (Maccullochella peeli peeli) and lettuce (Lactuca sativa). They found the highest production in the gravel bed (5.05 kg m⁻²), followed by floating rafts (4.47 kg m⁻²) and NFT (4.13 kg m⁻²) and no effect of hydroponic...
system on fish growth. Phosphate concentration in the water was not influenced by the hydroponics type (average value 3.6 mg L⁻¹), while the nitrate concentration was significantly higher in the NFT (15.7 mg L⁻¹) than in the other two systems (3.6 mg L⁻¹) with a lower nitrate-N removal efficiency in the NFT. Schmautz et al. (2016) compared tomato yield, morphological characteristics, biochemical characteristics and overall plant vitality in an AP using NFT, floating rafts, and drip irrigation with coconut fibre as substrate. Although the fruit quality was similar in all three systems, the tomato yield in the drip irrigation system was higher (18.7 kg m⁻²) than in NFT (17.5 kg m⁻²) and floating rafts (17.4 kg m⁻²). Goda et al. (2015) compared NFT with floating raft systems using different fish and plant species, showing that both systems were profitable. Moldovan and Băla (2015) compared medium-based and floating hydroponic systems using water from a pool populated by Carassius auratus. They concluded that the floating system is cheaper in construction and maintenance, whereas the medium-based system provides plants with added stability and can thus support larger plants.

Lennard and Leonard (2006) found the NFT system to be less efficient in terms of nutrient removal and lettuce yield than the medium-based or floating raft system Schmautz et al. (2016) obtained significantly lower tomato production in NFT than floating raft system but not than medium-based system. The lower nutrient removal capacity may be due to the restricted contact between the roots and the water. Plants grown in medium-based and floating hydroponic systems have their entire roots in contact with the water, providing them with more surface area to assimilate nitrate. In contrast, plant phosphate assimilation is not simply dependent upon the root area available to the water column (Lennard and Leonard, 2006) but also by water temperature (Adams, 1993) and pH (Raviv and Leith, 2008).

Nevertheless, NFT appears be an appropriate technology for aquaponics, based on capital cost and ease of use (Lennard and Leonard, 2006; Goda et al., 2015). Probably due to these reasons, some AP companies (i.e., UrbanFarmers, www.urbanfarmers.com) are using NFT channels for hydroponic section in commercial scale AP. Comparative studies are also rare, because researchers have more often used growth beds, whereas commercial operators more often use NFT. In view of these remarks, it would be desirable to conduct future research in commercial AP setting, in order to evaluate the performance of different soilless systems under realistic conditions.

### Substrate types

The most important requirement of a hydroponic growing medium is that it holds sufficient water and air to maintain optimal conditions for root and consequently plant growth (Hardgrave, 1995). Roosta and Afsharipoor (2012) evaluated the effect of different substrates (sole perlite, 75% perlite +25% cocopeat, 25% perlite +50% cocopeat, 25% perite +75% cocopeat, and sole cocopeat) on growth and development of strawberry plants in aquaponics with Grass carp (Ctenopharyngodon idella) and Silver carp (Hypophthalmichthys molitrix), concluding that the substrates with the higher percentage of perlite performed better. They also observed that: i) the lowest dry root weight was obtained from sole perlite and sole cocopeat; ii) the cocopeat (75:25) produced the highest number of runners; iii) SPAD index in young leaves decreased as the ratio of perlite to cocopeat decreased; iv) maximal quantum yield of PS II photochemistry (Fv/Fm) decreased with the increase of cocopeat to perlite ratio; v) sole perlite carried the highest number of fruits.

Buhmann et al. (2015) evaluated the effects of hydroponic sys-
sand (254 g m⁻²). The phosphorus (P) uptake was approximately three times higher in the floating system, while there were no differences between substrates in the medium-based system. The substrate did not influence chlorophyll or carotenoid content, whereas plants grown in the sand bed showed a significantly higher content of these molecules than plants grown in the floating system.

Sikawa and Yakupitiyage (2010) used nutrient rich catfish-pond water to produce lettuce and obtained higher head weight and yield in builders’ grade sand (0.10–0.25 mm in size) than in gravel (2.5 cm in size). Geisenhoff et al. (2016) compared the production of lettuce using two substrates in medium-based hydroponics (crushed stone vs flexible polyurethane foam) in an AP system with Nile tilapia (Oreochromis niloticus). They did not observe significant differences in lettuce productivity, with an average yield of 2.27 kg m⁻². On the other hand, flexible polyurethane foam resulted in higher concentrations of macro- and micronutrients in the shoot, a higher production of fresh shoot mass per plant (+10.8%) and more leaves (+22.1%) compared to the substrate with crushed stone. They attributed these results to reduced post-transplanting stress and to the increased water retention time provided by the flexible polyurethane foam. In addition, we hypothesize that the higher production with flexible polyurethane foam could be traced to the physical characteristics of this material that unlike crushed stone facilitate the penetration of the roots (Hardgrave, 1995) and increase both the root water contact time and exchange surface. Our hypothesis is also supported by the results of Buhmann et al. (2015) who obtained higher production with a more porous substrate (expanded clay), and by Sikawa and Yakupitiyage (2010), and Roosta and Afsharipoor (2012) who obtained higher production in the substrates with higher water retention capacities.

Rafiee and Saad (2006) investigated the effects of natural zeolite as a growth medium for lettuce in AP with red tilapia (Oreochromis sp.). They compared an AP system without zeolite as a control with one using a small cotton bag containing 10 g zeolite as a bed medium for a lettuce seeding. The presence of the zeolite exerted no significant effect on fish growth, while the lettuce yield was significantly higher (approximately 5.5 times). Furthermore, zeolite reduced the concentrations of inorganic N (−36.5%) and P (−17.9%) in the system water. Zeolites are characterised by high cation-exchange capabilities, and are thus able to adsorb ammonium-N (Nguyen and Tanner, 1998; Wang and Peng, 2010; Borin et al., 2013; Markou et al., 2014). In addition, iron- and aluminium-based crystalline and amorphous phases can become positively charged and, through a ligand exchange mechanism, their adsorption capabilities increase at neutral to acidic equilibrium pH values in comparison to alkaline conditions (Parfitt, 1979; Geelhoed et al., 1997). As a result, this zeolite was proposed as a P absorbent from wastewater (Wu et al., 2006). In AP systems, where ammonium (NH₄⁺) ions are continuously produced by fish and bacteria, the zeolite can adsorb these ions on its surface, and it can also act as substrate for nitrifying bacteria. In addition, organic acid released through root exudates can change pH values near the zeolite surface, increasing its capability to absorb P, an explanation that is supported by the results obtained by Rafiee and Saad (2006).

Crushed stones and river stones as substrate in AP with common carp (Cyprinus carpio) and mint (Mentha arvensis) have been compared by Shete et al. (2017) in terms of fish and plant growth, water quality, nutrient removal, and biofilter performance parameters concluding that the crushed stone medium was the most suitable. There is currently too little information available in the literature to draw conclusions about the effects of hydroponic substrate on AP. Nevertheless: i) zeolites appear as an interesting substrate for aquaponic systems for its capability to absorb nutrients and make these available for the roots; ii) there are some indications that the more porous substrate fosters plant nutrient uptake in AP, either by prolonging retention time with higher root-water contact time and/or providing attachment surface for microorganisms that solubilise nutrients.

**Water flow**

The water flow properties influence the contact time of the microorganisms and of roots with the water, which in turn influences both, the direct uptake of nutrients by plants, and the transformations by the microbial community (Effendi et al., 2015; Wahyuningsih et al., 2015).

**Continuous flow vs intermittent flow**

Intermittent cycles of flooding and draining in media filled beds provide uniform distribution of nutrients during the flood phase and improve aeration during the drain phase (McMurtry et al., 1997a). In continuous flow systems, high water retention time increases its contact time with roots and organisms, but it can lead to lower oxygenation rates and reduced nutrient availability. The complex removal mechanisms in the biofilter and the hydroponic component are similar to those of natural and constructed wetlands. In both, the removal of nutrients and/or pollutants is complex and depends on a variety of mechanisms, including sedimentation, filtration, precipitation, volatisation, adsorption, plant uptake, and various microbial processes (Wießner et al., 2005; Vymazal, 2007; Wu et al., 2014; Barbera et al., 2015; Maucieri et al., 2014, 2016).

Lennard and Leonard (2005) compared a reciprocating flood/drain cycle (10 min flood every 70 min) to a constant flow in a hydroponic gravel bed (0.52 m²) plated with lettuce during 21-day cycle. They obtained significantly higher lettuce yield (resulting in higher nitrate and phosphate assimilation), better pH buffering and higher dissolved oxygen concentrations in the constant flow.

In this context, species-specific responses to flow conditions should also be considered. Trang et al. (2010) studied the responses of Lactuca sativa, Ipomoea aquatica, Brassica rapa var. chinensis and Brassica rapa var. parachinensis to three root flooding conditions (drained, half-flooded and flooded) and observed that growth and performance of both Brassica varieties were best in the drained condition, while Lactuca sativa grew best in the half-flooded and Ipomoea aquatica in the flooded.

**Effects of water recirculation period**

Several authors investigated the effects of different water recirculation periods on AP systems performance in terms of water quality, fish and vegetables production.

Sreejiyari et al. (2016) tested three water recirculation regimes in a pilot AP system with hybrid tilapia (Oreochromis niloticus, O. mossambicus X O. hornorum X O. aureus) and lettuce (floating hydroponic): i) daytime recirculation, 11 h; ii) night time recirculation, 13 h; and iii) circadian recirculation, 24 h. The duration of the recirculation did not significantly influence water quality, lettuce growth and quality, suggesting that recirculation can be reduced from 24 h to 11-13 h.

Similarly, Shete et al. (2013a) investigated four recirculation periods (4, 8, 12, and 24 h day⁻¹) in a two-month trial, using a small aquaponic system with goldfish and spinach (Spinacea oler-
Non-commercial use only

Fish body weights were significantly higher at the two lower flow rates. The 1.5 L min⁻¹ flow rate produced significantly higher plants (24.3 cm) than the other two treatments (23.9 cm), however the flow rate exerted no significant effect on yield (average 1.24 kg m⁻²). The water nutrient content at the end of the experiment was not significantly different between the treatments except for potassium, whose concentration was significantly lower (14.3 mg L⁻¹) in the 1.5 L min⁻¹ flow rate than the other two flow rates (15.6 mg L⁻¹). Although flow rates showed similar performance in terms of fish growth, plant growth, and nutrient removal, the flow rate of 1.5 L min⁻¹ seemed to be the most effective for spinach and koi carp growth.

Dedić et al. (2012) evaluated water quality, sturgeon (initial density = 7.56 kg m⁻³) and lettuce (44 plants m⁻²) growth under two hydraulic regimes (Table 1). The 21-day trial was carried out in a micro AP (1.8 m²) with a floating raft system (0.55 m²). The oxygen concentration in the water at the higher flow rate (6.32 mg L⁻¹) was significantly higher than that at the lower one (5.89 mg L⁻¹), whereas an opposite trend was found for TAN (0.47 and 0.43 mg L⁻¹ with 8 and 16 L m⁻¹, respectively). Water flow did not influence nitrate and nitrite concentrations. Increasing the flow rate caused lower lettuce production and fish FCR and higher total fish weight gain and protein efficiency ratio (PER). Although Dedić et al. (2012) used a micro AP system, the data obtained were in line with bigger AP systems, indicating, as confirmed by Maučeri et al. (2018), that micro AP systems reliably mimic full-scale units.

In view of these results, and to maximise the performance of AP systems, a constant flow should be preferred to a reciprocating flood/drain cycle applied on an hourly level (e.g., 10 min flood every 70 min). Instead, if the water flow in the system is performed on a daily basis, recirculation can be reduced from 24 h to between 11 and 13 h, during the day or night. Halving the pump operation times has a positive influence on both economic and environmental considerations. Most of the papers examined suggest that from 2.3 to 18 fish tank water recirculations per day (Table 1) should be adopted to maximise system performance in terms of fish growth, plant growth and nutrients removal, but in many cases different water recirculation rates correspond to the same water flow (Endut et al., 2009, 2010; Nuwansi et al., 2016). Considering the above reported literature, the water flow speed through the roots bringing fresh molecules. The comparison of different water flows in root zone and hydraulic rates of the system water are summarised on the Table 1.

Very low constant flow rates were studied by Khater et al. (2015) (Table 1) in AP system consisting of five fish tanks (each 40 m³) and three gullies (each 27 m²) covered with foam rafts to support tomato plants. As flow rates increased, the authors observed an increase in plant nutrient uptake for N (+87.8%), P (+58.3%), K (+73.9%), Ca (+89.1%) and Mg (+74.3%) coupled with increase in root and shoot length and biomass, fruit yield per plant and also water use efficiency (from 5.54 to 7.16 kg m⁻³ as flow rate increased from 0.067 to 0.1 L min⁻¹). In a five-weeks trial, Endut et al. (2009, 2010) investigated different constant flow rates (Table 1) in an AP system with catfish (Clarias gariepinus; initial density = 25 kg m⁻³) and water spinach (100 plants m⁻²) planted in gravel-filled grow beds. The highest fish (45.7 kg m⁻³), and plant (17.9 kg m⁻³) production and the highest NO₃-N (64.9%), and TP (52.8%) removal were observed at 1.6 L min⁻¹, whereas the highest removal for BOD₅ (65.5%), TSS (82.9%), TAN (78.3%) and NO₃-N (89.5%) was found at 4.0 L min⁻¹. Assuming that the optimum hydraulic loading rate is determined by a compromise between fish and plant production, 1.6 L min⁻¹ can be considered the optimal water flow rate in this AP system (Endut et al., 2009, 2010). Similar flow rates, but with much higher complete fish tank water recirculation (Table 1) due to smaller fish tank volume were used by Nuwansi et al. (2016) in a 45-day experiment, which was conducted in a micro aquaponic system with a fish tank (70 L) with koi carp (Cyprinus carpio var. koi) and gold fish (Carassius auratus) and a gravel bed (100 L) planted with water spinach (28 plants m⁻²). Plant growth and nutrient removal increased as the flow rate decreased. The flow rate of 0.8 L min⁻¹ yielded the highest water spinach biomass and the highest fish weight gain coupled with the lowest feed conversion rate (FCR).

Hussain et al. (2015) experimented with constant flow rates (Table 1), in a small aquaponic system with Cyprinus carpio var. koi (initial density = 1.4 kg m⁻³) and Beta vulgaris var. bengalensis (spinach) (28 plants m⁻²) for a period of 45 days. The hydroponic section was split into two gravel (5-15 mm) beds each of 0.51 m².

Table 1. Tested water flows and fish tank water recirculations per day in different aquaponic systems.

<table>
<thead>
<tr>
<th>Water flow [L min⁻¹]</th>
<th>Fish tank water recirculation [number of recirculations per day]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8-1.6, 2.4-3.2, 4</td>
<td>1.2-2.3, 3.5-4.6, 5.8</td>
<td>Endut et al., 2009, 2010</td>
</tr>
<tr>
<td>8-16</td>
<td>43-85</td>
<td>Dedić et al., 2012</td>
</tr>
<tr>
<td>1.5-3.2</td>
<td>12-18, 32-4</td>
<td>Hussain et al., 2015</td>
</tr>
<tr>
<td>0.067-0.083, 0.1</td>
<td>Cannot be calculated</td>
<td>Khater et al., 2015</td>
</tr>
<tr>
<td>0.8-2.4</td>
<td>16.5-49.4, 82.3</td>
<td>Nuwansi et al., 2016</td>
</tr>
<tr>
<td>4.2-8.3-10.7</td>
<td>12-24, 48</td>
<td>Shete et al., 2016*</td>
</tr>
<tr>
<td>0.35-1.4, 2.8</td>
<td>0.5-2.4</td>
<td>Diem et al., 2017</td>
</tr>
</tbody>
</table>

*The study is not discussed because results are obtained in a system with a very low fish density (Cyprinus carpio; initial density = 30 g m⁻³) that determine low ions concentration. Italics values are the best solution for each paper.
densities, different hydroponic systems and plant species. Therefore, more studies are needed to confirm this assumption.

Water consumption

Fish farming requires a huge input of good quality water and discharges low quality water into the environment (Sauthier et al., 1998; De Stefani et al., 2011). Therefore, both the reduction of water input and the treatment of aquaculture effluent equally are important because water is a limited resource and effluent nutrient discharge can contribute to environmental degradation (Adler et al., 2000b).

Water exchange is the most effective and widely employed method for maintaining good water quality in aquaculture farms (Masser et al., 1999). The exchange rate varies from as high as 250% per day for extensive aquaculture to between 2 and 10% per day for intensive aquaculture systems (Adler et al., 1998; De Stefani et al., 2000b).

Figure 5. Hydroponic:fish tank ratio (m² m⁻³) and aquaponics system water replacement (%) correlation. Circular markers are referred at McMurtry et al. (1997b) paper, square markers are referred at all other reviewed papers except outlier water replacement values of Graber and Junge (2009).

Table 2. Aquaponic system characteristics and daily water consumption.

<table>
<thead>
<tr>
<th>Hydroponic Type</th>
<th>Fish Species</th>
<th>Plant Species</th>
<th>Water Flow</th>
<th>Water Temperature (°C)</th>
<th>Water Consumption (%)</th>
<th>Hydroponic/Fish Tank Ratio (m² m⁻³)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floating</td>
<td>Oreochromis niloticus</td>
<td>I. aquatica</td>
<td>Constant</td>
<td>27.5</td>
<td>1.40</td>
<td>1.9</td>
<td>Danaher et al., 2013</td>
</tr>
<tr>
<td></td>
<td>Oreochromis niloticus</td>
<td>I. aquatica</td>
<td>Constant</td>
<td>27.4</td>
<td>1.50</td>
<td>1.9</td>
<td>Danaher et al., 2011</td>
</tr>
<tr>
<td></td>
<td>Clarias gariepinus</td>
<td>I. aquatica</td>
<td>Constant</td>
<td>26.3</td>
<td>1.60</td>
<td>1.9</td>
<td>Endut et al., 2014</td>
</tr>
<tr>
<td></td>
<td>Oreochromis niloticus</td>
<td>L. esculentum</td>
<td>Constant</td>
<td>26.1</td>
<td>1.60</td>
<td>1.9</td>
<td>Hu et al., 2015</td>
</tr>
<tr>
<td></td>
<td>Clarias gariepinus</td>
<td>I. aquatica</td>
<td>Constant</td>
<td>26.2</td>
<td>1.60</td>
<td>1.9</td>
<td>Endut et al., 2016</td>
</tr>
<tr>
<td></td>
<td>Maccullochella peelii peelii</td>
<td>L. sativa</td>
<td>Constant</td>
<td>22</td>
<td>&lt;5</td>
<td>1.7</td>
<td>Leonard and Leonard, 2006</td>
</tr>
<tr>
<td></td>
<td>Oreochromis spp.</td>
<td>O. basilicum</td>
<td>Constant</td>
<td>26.5</td>
<td>2.40</td>
<td>6.9</td>
<td>Raloczy et al., 2003</td>
</tr>
<tr>
<td></td>
<td>Oreochromis niloticus, Oreochromis auratus, Oreochromis sp.</td>
<td>Crop succession for 2 years</td>
<td>Constant</td>
<td>&gt;22</td>
<td>1.83</td>
<td>5.2</td>
<td>Love et al., 2015</td>
</tr>
<tr>
<td></td>
<td>Oreochromis niloticus, Misgurnus anguillicandatus</td>
<td>L. sativa</td>
<td>Root in fish tank</td>
<td>29.6</td>
<td>0.10</td>
<td>1.2</td>
<td>Liang and Chien, 2013</td>
</tr>
<tr>
<td></td>
<td>Maccullochella peeltii peeltii</td>
<td>L. sativa</td>
<td>Root in fish tank</td>
<td>25.4</td>
<td>1.00</td>
<td>1.3</td>
<td>Liang and Chien, 2015</td>
</tr>
<tr>
<td>Medium-based</td>
<td>Maccullochella peeltii peeltii</td>
<td>L. sativa</td>
<td>Reciprocal</td>
<td>22</td>
<td>2.86</td>
<td>5.2</td>
<td>Leonard and Leonard, 2005</td>
</tr>
<tr>
<td></td>
<td>Cyprinus carpio var koi</td>
<td>B. vulgaris var bengalensis</td>
<td>Constant</td>
<td>26.3</td>
<td>4</td>
<td>2.8</td>
<td>Hussain et al., 2015</td>
</tr>
<tr>
<td></td>
<td>Cyprinus carpio</td>
<td>B. chinesis</td>
<td>Constant</td>
<td>23</td>
<td>1.80</td>
<td>3.5</td>
<td>Zou et al., 2016</td>
</tr>
<tr>
<td></td>
<td>Cyprinus carpio</td>
<td>B. chinesis</td>
<td>Constant</td>
<td>26.9</td>
<td>1.20</td>
<td>4.4</td>
<td>Zou et al., 2016a</td>
</tr>
<tr>
<td></td>
<td>Oreochromis niloticus</td>
<td>S. melonega</td>
<td>Constant</td>
<td>27.9</td>
<td>0.36</td>
<td>6.9</td>
<td>Raloczy et al., 2004</td>
</tr>
<tr>
<td></td>
<td>Perca fluviatilis</td>
<td>L. esculentum</td>
<td>Constant</td>
<td>21</td>
<td>1.83</td>
<td>5.2</td>
<td>Graber and Junge, 2009</td>
</tr>
<tr>
<td></td>
<td>C. satrasi</td>
<td>L. esculentum</td>
<td>Constant</td>
<td>26.3</td>
<td>2.80</td>
<td>2.1</td>
<td>Leonard and Leonard, 2006</td>
</tr>
<tr>
<td></td>
<td>Maccullochella peeltii peeltii</td>
<td>L. sativa</td>
<td>Root in fish tank</td>
<td>25.4</td>
<td>1.00</td>
<td>1.3</td>
<td>Liang and Chien, 2015</td>
</tr>
<tr>
<td></td>
<td>Tilapia mossambicus x L. niloticus</td>
<td>L. esculentum, C. satrasi</td>
<td>Constant</td>
<td>&gt;25</td>
<td>2.80</td>
<td>4.1</td>
<td>McMurtry et al., 1997a</td>
</tr>
<tr>
<td></td>
<td>Tilapia mossambicus x L. niloticus</td>
<td>L. esculentum</td>
<td>Constant</td>
<td>&gt;25</td>
<td>2.08</td>
<td>2.1</td>
<td>McMurtry et al., 1997b</td>
</tr>
<tr>
<td></td>
<td>Tilapia mossambicus x L. niloticus</td>
<td>L. esculentum</td>
<td>Constant</td>
<td>&gt;25</td>
<td>2.42</td>
<td>3.0</td>
<td>McMurtry et al., 1997b</td>
</tr>
<tr>
<td></td>
<td>Tilapia mossambicus x L. niloticus</td>
<td>L. esculentum</td>
<td>Constant</td>
<td>&gt;25</td>
<td>2.84</td>
<td>4.6</td>
<td>McMurtry et al., 1997b</td>
</tr>
<tr>
<td></td>
<td>Tilapia mossambicus x L. niloticus</td>
<td>L. esculentum</td>
<td>Constant</td>
<td>&gt;25</td>
<td>3.88</td>
<td>7.0</td>
<td>McMurtry et al., 1997b</td>
</tr>
<tr>
<td>NFT</td>
<td>Oreochromis niloticus</td>
<td>L. esculentum</td>
<td>Constant</td>
<td>25</td>
<td>3.83</td>
<td>1.4</td>
<td>Klaas et al., 2015</td>
</tr>
<tr>
<td></td>
<td>Oreochromis niloticus</td>
<td>C. satrasi, L. sativa</td>
<td>Constant</td>
<td>29.1</td>
<td>0.90</td>
<td>1.2</td>
<td>Castillo-Castellanos et al., 2016</td>
</tr>
<tr>
<td></td>
<td>Oreochromis niloticus</td>
<td>L. sativa</td>
<td>Constant</td>
<td>28</td>
<td>1.40</td>
<td>28.4</td>
<td>Al-Hafedh et al., 2008</td>
</tr>
<tr>
<td></td>
<td>Maccullochella peeltii peeltii</td>
<td>L. sativa</td>
<td>Constant</td>
<td>22</td>
<td>1.97</td>
<td>5.2</td>
<td>Leonard and Leonard, 2006</td>
</tr>
</tbody>
</table>
day for intensive aquaculture (Hu et al., 2015) and less than 1% for modern closed recirculating aquaculture systems (RAS) (Turcios and Papenbrock, 2014). Bildariu and Grozea (2011) define RAS as aquaculture systems that incorporate the treatment and reuse of water while replacing less than 10% of the total water volume per day. AP systems can be considered a type of RAS. Water is usually treated by mechanical and biological filtration, although additional water treatment elements (e.g., ultraviolet irradiation, ozonation) may be included (Hutchinson et al., 2004).

Daily water loss in AP systems is caused by fish sludge removal, evaporation, plant evapotranspiration, and fish splashing during feeding. These losses range from 0.05% (Goda et al., 2015) to 5% (Endut et al., 2014, 2016) of total water, although higher values (9%-41%) have been found in particular conditions (Graber and Junge, 2009) (Table 2). The daily water loss is influenced among others (temperature, biofilter construction, greenhouse conditions) by the hydroponic surface/fish tank volume ratio. Increasing the hydroponic surface/fish tank volume ratio from 0.67 to 2.25 augmented the daily water replacement from 1.2% to 4.7% (McMurtry et al., 1997b). Lennard and Leonard (2005) measured an average daily consumption of 2.65% in an AP system with a medium-based hydroponic bed planted with L. sativa for 21 days and observed no influence of the management of the hydroponic section (reciprocating flood/drain cycle vs. constant flow) on the water. Also, the type of hydroponics (gravel, floating or NFT) had no influence on water loss (Lennard and Leonard, 2006) (Table 2).

Plant evapotranspiration is the most important factor that determines water loss. Graber and Junge (2009) observed a daily water loss of 9%, 15%, and 41% with cucumber, aubergine and tomato, respectively. Hu et al. (2015) measured a daily water loss of 0.7%, and 2.2% with pak choi, and tomato, respectively. The differences in the values for the tomato culture can be probably attributed to the higher hydroponic surface/fish tank volume ratio used by Graber and Junge (2009). No correlation was found between the hydroponic unit surface/fish tank volume ratio and the water loss across the different studies (Table 2, Figure 5). However, when the data were obtained in the same experiment (McMurtry et al., 1997b) the correlation was strongly positive (Figure 5); increasing the hydroponic unit surface/fish tank volume ratio of 3.4 times the water loss increased of 1.9 times. In view of this, although further research is needed to confirm the above reported findings, the daily water loss in the AP system is primarily influenced by the hydroponic surface/fish tank volume ratio and by the plant species used in the hydroponic section. There is no significant effect exerted by hydroponic section management (reciprocating flood/drain cycle or constant flow) or type (gravel, floating or NFT).

Conclusions

No unequivocal results have been found for hydroponic system types in AP in terms of yield and water quality. However, many companies are using NFT channels for hydroponic section in full-scale aquaponic systems, probably due to the easier management than other soilless systems. In view of this, further studies are desirable for a more comprehensive evaluation of hydroponic systems efficiency in the aquaponic systems. In terms of substrate characteristics in the medium-based technique, too little information is available in the literature to reliably identify the best performing substrate. However, the literature review suggests that more porous substrates should be preferred to maximise aquaponic systems performance.

To maximise the performance of AP systems, constant flow should be preferred to a reciprocating flood/drain cycle, if the systems are managed on a hourly basis (e.g., 10 min flood every 70 min). Instead, if the water flow in the system is managed on a daily basis (one continued recirculation for several hours each day), recirculation can be reduced from 24 h to 11-13 h during either the day or night. The halving of the pump operation time has a positive influence on both economic and environmental aspects. Most of the papers suggest that between 2.3 and 18 fish tank water recirculations per day with a water flow from 0.8 L min⁻¹ (0.048 m³ h⁻¹) to 8.0 L min⁻¹ (0.48 m³ h⁻¹) should maximise aquaponic system performance in terms of fish growth, plant growth and nutrients removal. Comparing information about water recirculation and water flow in the analysed literature, flow results more important for maximizing system performance although this arises from a few studies carried out with different fish species and density, different hydroponic systems and therefore further investigations are needed.

Daily water loss in the AP systems is primarily influenced by hydroponic surface/fish tank volume ratio and by the plant species used in the hydroponic section. No significant effect is exerted by hydroponic section management (reciprocating flood/drain cycle or constant flow) or type (gravel, floating or NFT).

References


Hussain T, Verma AK, Tiwari VK, Prakash C, Rathore G, Shete AP, Saharan N, 2015. Effect of water flow rates on growth of...


