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Hydroponic systems and water management in aquaponics: a review

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Abstract

Aquaponics, 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 (reciprocating flood/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; Medina *et al.*, 2016, Nichols and Savidov, 2012; Nuwansi *et al.*, 2016). AP has received considerable attention due to its capability to sustain water quality, minimize 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 volatilization (CO_2, CH_4, N_2, N_2O, NH_3, etc.) by the same processes as in constructed wetlands (Mander *et al.*, 2014; Maucieri *et al.*, 2017a).

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).

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 (Yavuzcan 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 summarize 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: 1) cultivation systems without substrate that include the Nutrient Film Technique (NFT) (Cooper, 1979) and different types of floating raft systems; 2) medium based systems, where a certain volume of substrate ensures roots anchorage, and acts as substrate for microorganisms' attachment and water-nutritional flywheel. These last systems can be further distinguished on the basis of substrate used: organic, inorganic and synthetic (Enzo *et al.*, 2001) (Figure 1).

The choice of hydroponic type for an AP may be based on the independent advantages conferred by any particular hydroponic component (Lennard and Leonard, 2006) or on LCA impact (Forchino *et al.*, 2017). All the methods represented in Figure 1 can be integrated in an aquaponic system (Pattillo, 2017). However, the choice influences the design of the whole 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 could be useful to maximize 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 1. 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 used species (Figure 4).

Only 7% 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 peelii peelii)* 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 type of hydroponics (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 *Cariassus 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.

According to the results of Lennard and Leonard (2006), the NFT system is less efficient in terms of nutrient removal and lettuce yield than the medium-based or floating raft system whereas 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 opportunity 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 research 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 in real conditions.

Substrate types

The most important requirement of a hydroponic growing medium is that it holds sufficient water and air to maintain optimum 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, 50% perlite + 50% cocopeat, 25% perlite + 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 system (medium-based vs floating), and substrate type (expanded clay vs sand) on *Tripolium pannonicum* (Jacq.) Dobrocz. using artificial seawater. Neither the hydroponic system nor the substrate influenced the fresh biomass weight or N uptake, whereas expanded clay provided a significantly higher (+54.1%) dry matter production than sand (254.2 g m^{-2}). The 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 carotenoids 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 (*Lactuca sativa)* 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 aquaponic 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 aquaponic system without zeolite as a control with one using a small cotton bag containing 10 g zeolite as a bed medium for a lettuce seedling. 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 characterized 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 an absorbent for phosphorus (P) from wastewater (Wu *et al.*, 2006). In AP systems, where NH_4^+ 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: 1) zeolites appear as an interesting substrate for aquaponic systems for its capability to absorb nutrients and make these available for the roots; 2) 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 solubilize 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 improved 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, volatilization, 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 m^2) plated with lettuce (*Lactuca sativa*) 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 *Ipomea aquatica* in the flooded.

Effects of water recirculation period

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

Sreejariya *et al.* (2016) tested three water recirculation regimes in a pilot AP with hybrid tilapia (*Oreochromis niloticus*, *O. mossambicus* X *O. hornorum* X *O. aureus*) and lettuce (*Lactuca sativa*) (floating hydroponic): 1) daytime recirculation, 11 hours; 2) night time recirculation, 13 hours; and 3) circadian recirculation, 24 hours. The duration of the recirculation did not significantly influence water quality, lettuce growth and quality, suggesting that recirculation can be reduced from 24 hours to 11-13 hours.

Similarly, Shete *et al.* (2013a) investigated four recirculation periods (4, 8, 12, and 24 hrs day^{-1}) in a two-month trial, using a small aquaponic system with goldfish and spinach (*Spinacea oleracea*). No significant differences in levels of total ammonium nitrogen (TAN), nitrite nitrogen (NO_2-N), and nitrate nitrogen (NO_3-N) were found among the four treatments. On the other hand, the fish growth was the highest under the 24 hours recirculation and decreased with decreasing recirculation periods. There were no significant differences in spinach growth among the treatments; though the leaf chlorophyll content significantly decreased with decreased recirculation time, which could be caused by the lower nutrient availability. Even if the nutrient levels in the water were not significantly different, longer recirculation probably prevented the formation of micro-gradients around the roots, where nutrient depletion occurs on a very small spatial scale. They concluded that the optimal water circulation period was 12 hrs day^{-1}. Although the water N content detected in this study was lower than the reportedly optimal values for hydroponics (Pantanella *et al.*, 2012; Bittsanszky *et al.*, 2016; Delaide *et al.*, 2016), this did not have a significant effect on crop yield.

In addition to water recirculation periods, water flow and hydraulic rate are major factors in AP systems performance. The optimization of these parameters in AP is important considering that if low hydraulic load rate leads to oxygen deficiency and enables denitrification and N_2 volatilization, high hydraulic load rate reduces the contact time between water and roots with (Wongkiew et al., 2017). A question arises as to whether it is more important the water recirculation frequency in the fish tanks or 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 summarized on the Table 1.

Very low constant flow rates were studied by Khater *et al.* (2015) (Table 1) in AP consisting of five fish tanks (each 40 m^3) and three gullies (each 27 m^2) covered with foam rafts to support tomato (*Lycopersicum esculentum*) 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 with catfish (*Clarius gariepinus*; initial density = 25 kg m^{-3}) and water spinach (*I. aquatica*; 100 plants m^{-2}) planted in gravel-filled grow beds. The highest fish (45.7 kg m^{-3}), and plant (17.9 kg bed^{-1}) production and the highest NO_3-N (64.9%), and TP (52.8%) removal were observed at 1.6 L min^{-1}, whereas the highest removal for BOD_5 (65.5%), TSS (82.9%), TAN (78.3%) and NO_2-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 (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 (70L) with koi carp (*Cyprinus carpio* var. *koi*) and gold fish (*Carassius auratus*) and a gravel bed (100L) planted with water spinach (*Ipomea aquatica*; 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 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 m^2. 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.

Dediu *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 m^3) with a floating raft system (0.55 m^2). 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 nitrite and nitrate concentrations. Increasing the water flow caused lower lettuce production and fish FCR and higher total fish weight gain and PER. Although Dediu *et al.* (2012) used a micro AP system, the data obtained were in line with bigger AP systems, indicating, as confirmed by Maucieri *et al.* (2017b), that micro AP systems reliably mimic full-scale units.

In view of these results, and to maximize the performance of aquaponic systems, a constant flow should be preferred to a reciprocating flood/drain cycle applied on an hourly level (e.g. 10 minute flood every 70 minutes). Instead, if the water flow in the system is performed on a daily basis, recirculation can be reduced from 24 hours to between 11 and 13 hours, 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 maximize 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 (e.g. Endut *et al.*, 2009, 2010 and Nuwansi *et al.*, 2016). Considering the above reported literature, the water flow speed through the roots bringing fresh molecules is of greatest importance, with better performance between 0.8 L min^{-1} and 8.0 L min^{-1} (Table 1). However, this conclusion results from very few studies carried out with different (oft too low) fish 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 (Hu *et al.*, 2015) and less than 1% for modern closed recirculating aquaculture systems (RAS) (Turcios and Papenbrock, 2014). Blidariu 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. Aquaponic 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 aquaponic 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 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 aquaponic systems 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 maximize aquaponic systems performance.

To maximize the performance of AP systems, constant flow should be preferred to a reciprocating flood/drain cycle, if the system are managed on a hourly basis (e.g. 10 minutes flood every 70 minutes). 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 hours to 11-13 hours 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 recirculations per day with a water flow from 0.8 L min^{-1} (0.048 m^3 h^{-1}) to 8.0 L min^{-1} (0.48 m^3 h^{-1}) should maximize 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 aquaponic 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).

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Figure 1. Schematic configuration of the most frequently used hydroponic cultivation systems.

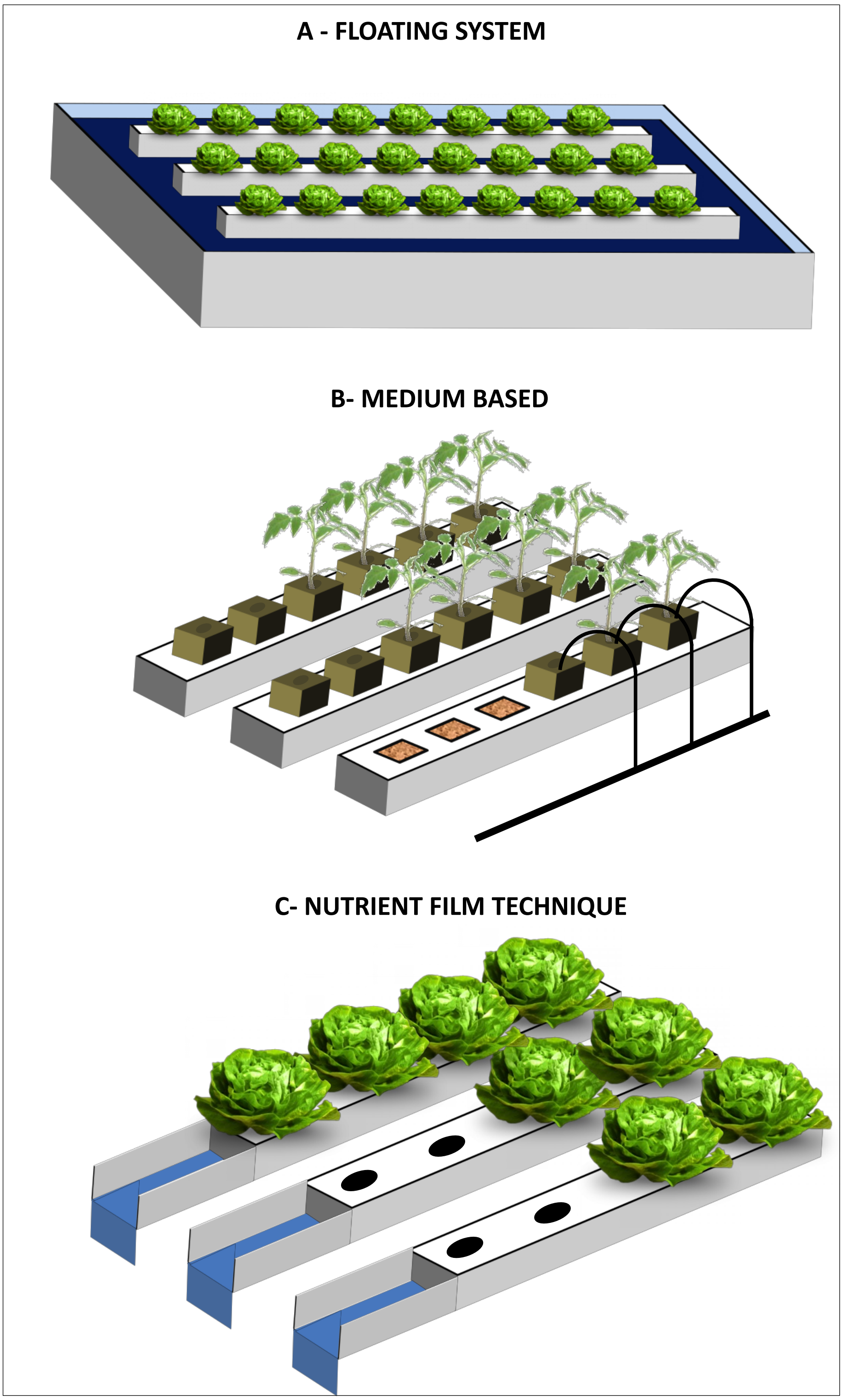

Figure 2. Percentage of papers for each type of hydroponics implemented in aquaponic systems (Total number of papers: 58).

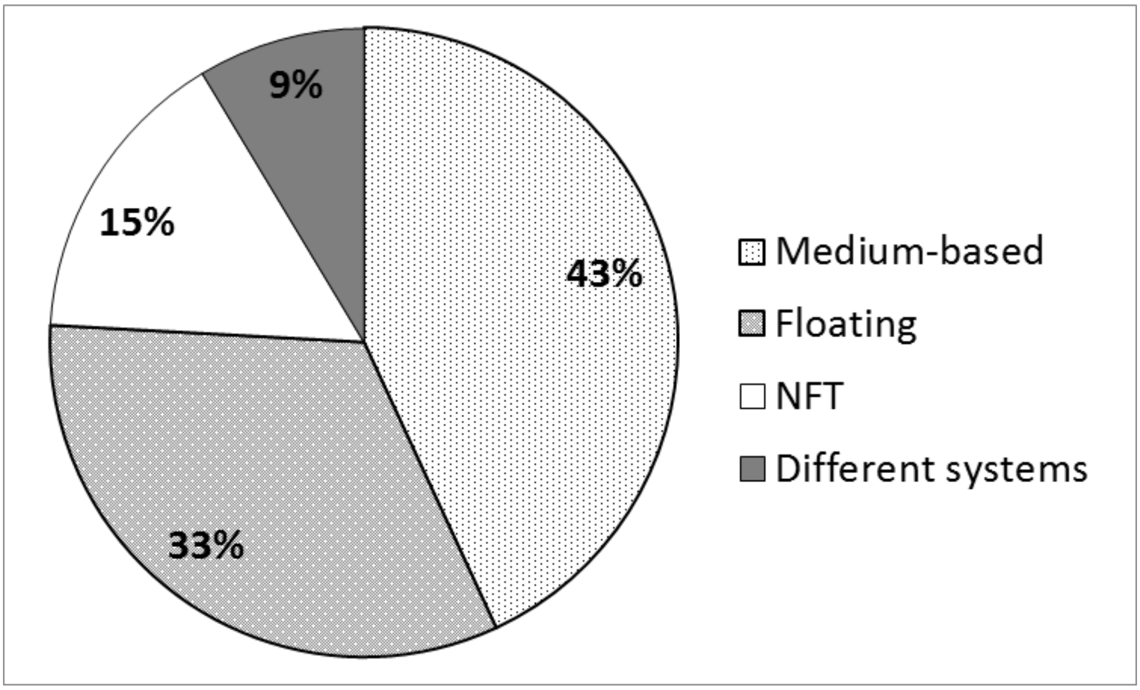

Figure 3. Number of papers that report results on one or more than one species and used hydroponic system.

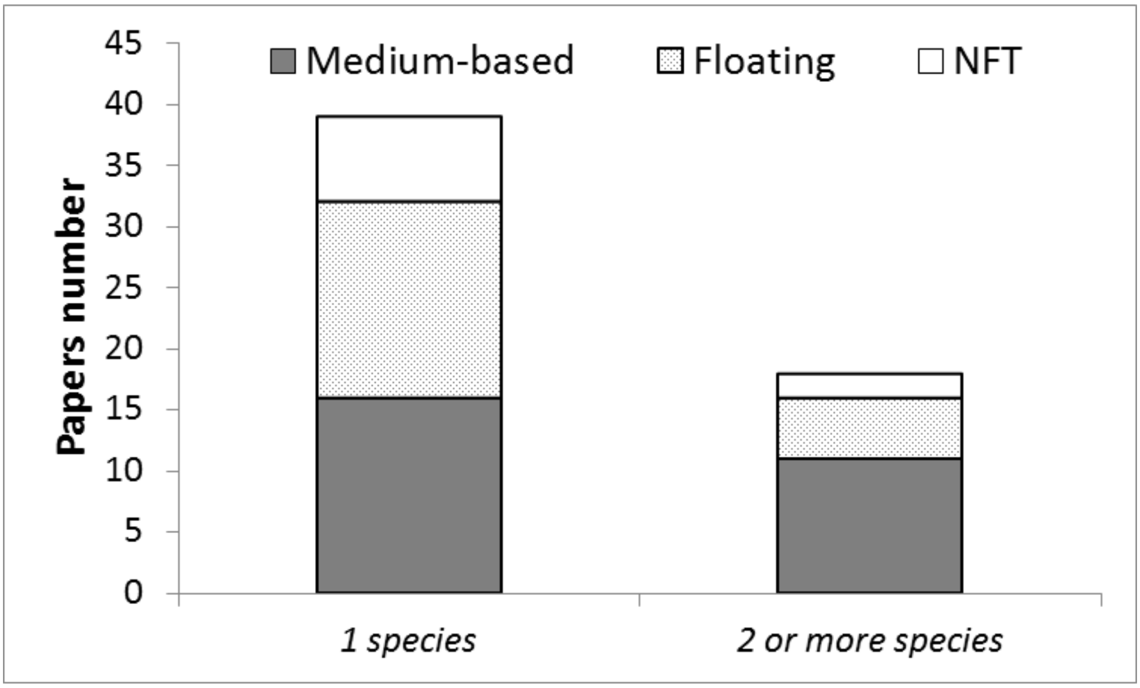

Figure 4. Plant species used in aquaponic systems with different hydroponic unit.

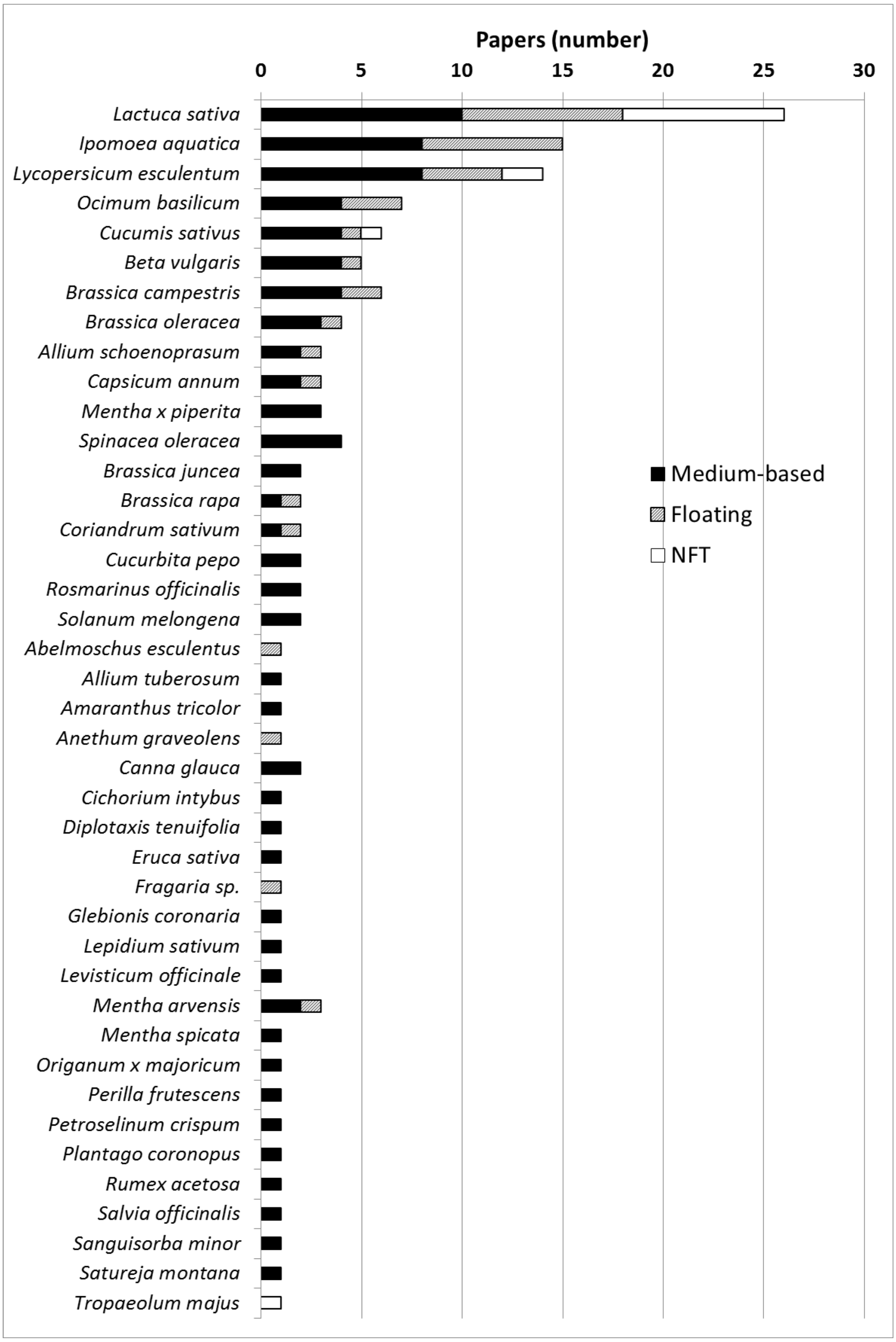

Figure 5. Hydroponic:fish tank ratio (m^2 m^{-3}) and aquaponics system water replacement (%) correlation. Circular markers are referred at McMurtry et al. (1997b) paper,

square markers are referred at all other reviewed papers except outlier water replacement values of Graber and Junge (2009).

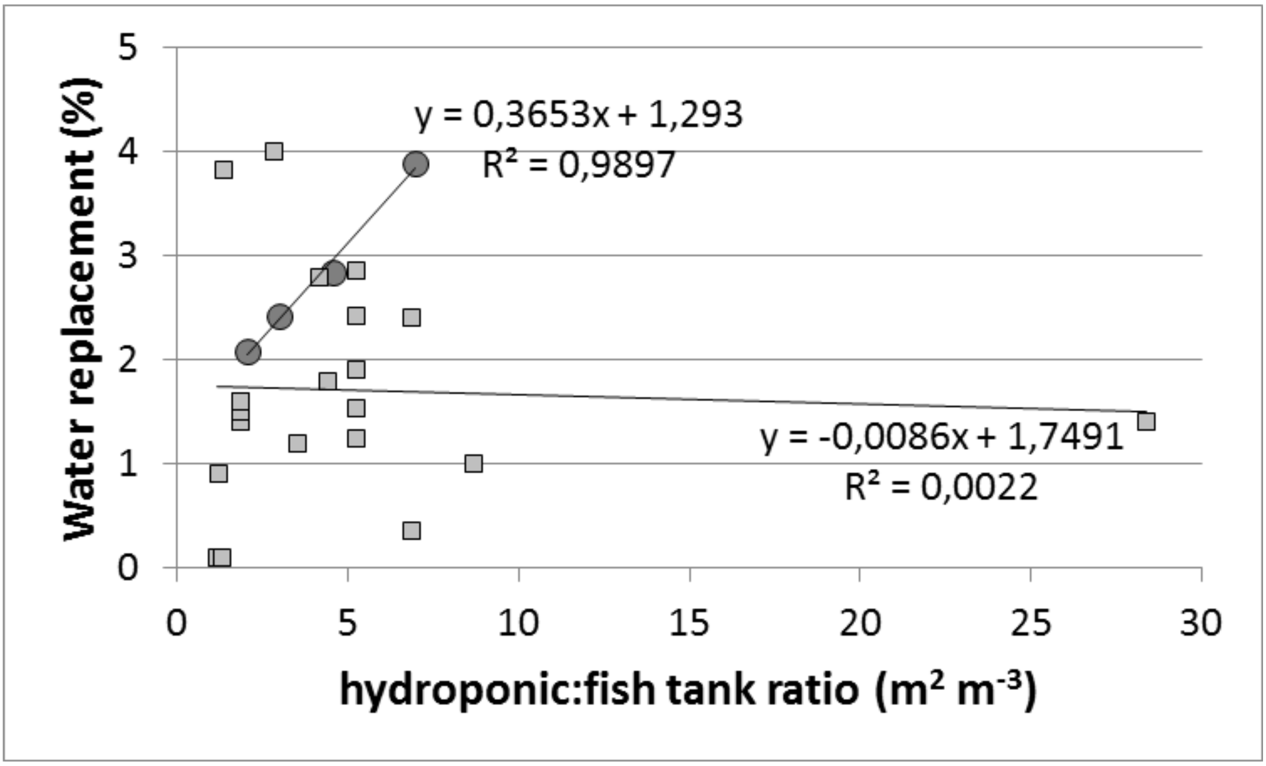

Table 1. Tested water flows (a) and fish tank water recirculations per day (b) in different aquaponic systems. Bold values are the best solution for each paper.

Water flow [L min^{-1}]	**Fish tank water recirculation [number of recirculations per day]**	**Reference**
0.8 – **1.6** – 2.4 – 3.2 – 4	1.2 – **2.3** – 3.5 – 4.6 – 5.8	Endut et al., 2009, 2010
8 – 16	**43** – 86	Dediu et al., 2012
1 – **1.5** – 3,2	12 – **18** – 32,4	Hussain et al., 2015
0.067 – 0.083 – **0.1**	Cannot be calculated	Khater et al., 2015
0.8 – 2.4 – 4	**16.5** – 49.4 – 82.3	Nuwansi et al., 2016
4.2 – **8.3** – 16.7	12 – **24** – 48	Shete et al., 2016*
0.35 – **1.4** – **2.8**	0.5 – **2** – **4**	Diem et al., 2017

* The study is not discussed because results are obtained in a system with a very low fish density (*Cyprinus carpio*; initial density = 90 g m^{-3}) that determine low ions concentration.

Table 2. Aquaponic system characteristics and daily water consumption.

Hydroponic type	**Fish species**	**Plant species**	**Water flow**	**Water temperature (°C)**	**Water consumption (%)**	**Hydroponic/Fish tank ratio (m^2 m^{-3})**	**Reference**
Floating	*Oreochromis niloticus*	*I. aquatica*	Constant	27.5	1.40	1.9	Danaher et al., 2013
				27.4	1.50	1.9	
	Oreochromis	*I. aquatica*	Constant	26.3	1.60	1.9	Danaher et al., 2011

	niloticus			26.1	1.60	1.9	
	Clarias gariepinus	*I. aquatica*	Constant	29	<5	1.6	Endut et al., 2014
	Oreochromis niloticus	*L. esculentum*	Constant	26	2.2		Hu et al., 2015
		B. campestris L. subsp. Chinensis		26.2	0.70		
	Clarias gariepinus	*I. aquatica, B. juncea*	Constant		<5	1.7	Endut et al., 2016
	Maccullochella peelii peelii	*L. sativa*	Constant	22	1.83	5.2	Lennard and Leonard, 2006
	Oreochromis spp.	*O. basilicum*	Constant	26.5	2.40	6.9	Rakocy et al., 2003
	Oreochromis spp.	*Abelmoschus esculentus*	Constant	27.9	0.36	6.9	Rakocy et al., 2004
	Oreochromis niloticus, Oreochromis aureus	Crop succession for 2 years	Constant	>22	1	8.7	Love et al., 2015
	Oreochromis sp.	*I. aquatica*	Root in fish tank	29.6	0.10	1.2	Liang and Chien, 2013
	Misgurnus anguillicandatus	*Asplenium nidus*	Root in fish tank	25.4	0.10	1.3	Liang and Chien, 2015
Medium-based	*Maccullochella peelii peelii*	*L. sativa*	Reciprocal	22	2.86	5.2	Lennard and Leonard, 2005
			Constant	22	2.43	5.2	

	Cyprinus carpio var. koi	*B. vulgaris var. bengalensis*	Constant	26.3	4	2.8	Hussain et al., 2015
	Cyprinus carpio	*B. chinensis*	Constant	23	1.80	3.5	Zou et al., 2016b
	Cyprinus carpio	*B. chinensis*	Constant	26.9	1.20	4.4	Zou et al., 2016a
	Oreochromis niloticus	*S. melongena*	Constant		15	2.1	Graber and Junge, 2009
	Perca fluviatilis	*L. esculentum*	Constant		41	2.1	
		C. sativus			9	2.1	
	Maccullochella peelii peelii	*L. sativa*	Constant	22	1.73	5.2	Lennard and Leonard, 2006
	Tilapia mossambicus x 0. niloticus	*L. esculentum, C. sativus*	Constant	>25	2.80	4.1	McMurtry et al., 1997a
	Tilapia mossambicus x 0. niloticus	*L. esculentum*	Constant	>25	2.08	2.1	McMurtry et al., 1997b
	Tilapia mossambicus x 0. niloticus	*L. esculentum*	Constant	>25	2.42	3.0	
	Tilapia mossambicus x 0.	*L. esculentum*	Constant	>25	2.84	4.6	

	niloticus						
	Tilapia mossambicus x 0. niloticus	*L. esculentum*	Constant	>25	3.89	7.0	
NFT	*Oreochromis niloticus*	*L. esculentum*	Constant	25	3.83	1.4	Kloas et al., 2015
	Oreochromis niloticus	*C. sativus, L. sativa*	Constant	29.1	0.90	1.2	Castillo-Castellanos et al., 2016
	Oreochromis niloticus	*L. sativa*	Constant	28	1.40	28.4	Al-Hafedh et al., 2008
	Maccullochella peelii peelii	*L. sativa*	Constant	22	1.97	5.2	Lennard and Leonard, 2006