Suitability and optimization of FAO's small-scale aquaponics systems for joint production of lettuce (*Lactuca sativa*) and fish (*Carassius auratus*)

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Abstract

Aquaponics is a developing technique that combines the simultaneous production of plants (hydroponics) and fish (aquaculture). With it, the use of resources (i.e., water, nutrients, land) is reduced whilst at the same time minimising residues' discharge to the environment. Among its benefits, it allows the production of healthy vegetables and fish in reduced spaces by means of small-scale systems. In this work, three of them based on FAO models with different hydroponic subsystems (nutrient film technique -NFT-, floating raft, and vertical felt) are tested to produce lettuce (*Lactuca sativa*) and goldfish (*Carassius auratus*). Water parameters as well as the growth of plants and fishes were monitored in two different production cycles. The hydroponic subsystem that outperformed the best was the NFT, both in terms of crop production and water consumption. All systems showed similar results in fish production. Further research is needed to corroborate the outputs obtained when using other combinations of plants and fishes. Small-scale aquaponic systems are particularly interesting for self-production and even more so in urban environments with reduced available space.

Keywords: Aquaponics, sustainable production, aquaculture, hydroponics

Abbreviations

AGR: absolute growth rate

AP: aquaponics

AWF: average weight per fish

DMC: dry matter content

DWC: daily water consumption

DWP: dry weight per plant

FCR: feed conversion ratio

FI: feed intake

FWP: fresh weight per plant

LB: Lollo bionda lettuce

LR: Lollo rosso lettuce

RL: romaine lettuce

SAS: small-scale aquaponic system

SGR: specific growth rate

SVR: survival rate

T_{max}: maximum water temperature

T_{min}: minimum water temperature

TFW: total fresh weight of lettuce shoots

TWC: total volume of water used

TW: total weight of fishes

WR: water replenishment rate

1. Introduction

Aquaponics (AP) can be defined as a technique that synergistically combines the simultaneous production of plants (hydroponics) and fish (aquaculture), for commercial, domestic, ornamental or educational purposes. This is achieved by a continuous recirculation of water through both subsystems. Plants improve their growth by using metabolic waste from fish and unconsumed feed, which are transformed by a bacterial community into easily assimilated nutrients (i.e., nitrates, phosphates). Due to the extraction made by the plants' root system, water is purified from excessive nitrates and phosphates, maintaining adequate levels for fish development (Rakocy et al., 2006).

AP reproduces under controlled conditions the natural cycle of the mineralisation of organic matter in nature that allows the cleansing of water bodies throughout the planet and maintains a beneficial balance for all living beings. For this reason, AP is presented as an interesting alternative for the implementation of productive systems based on a circular economy (reduce, reuse, recycle), as opposed to the classic ones based on a linear economy (extraction, manufacture, use, dispose). This technique has a positive environmental impact as it avoids some of the problems associated with conventional aquaculture (a potential contamination of aquifers with effluents, water requirements/water footprint, wastewater treatment cost, etc.) and agriculture (a limitation of fertilisers such as phosphorus, water footprint, an excessive use of pesticides and fossil fuels, soil contaminants/diseases, etc.). Therefore, AP aims to reduce inputs as well as to minimise pollution (e.g., wastewater) (Blidariu and Grozea, 2011) whilst maximising production efficiency and stability, hence increasing revenues (Tyson et al., 2011).

For instance, compared to conventional agriculture, AP uses less than 10% of water, depending on the climatic conditions (Bernstein, 2011). Around 1–3 % of its total water volume per day has to be replenished (Somerville et al., 2014). This is an advantage compared to 5-10% for recirculating aquaculture (Timmons et al., 2007). AP also involves a lower use in fertiliser than conventional or hydroponic systems (Tyson et al., 2009).

Nowadays, AP can be considered an emerging technology and developing science topic (König et al., 2018) contributing to more sustainable food systems (Goddek et al., 2015) in different settings – urban/rural, small/large scale, developed/developing countries (Junge et al., 2017). Consequently, this sustainable production of fresh fish and vegetables using intensive technological cycle systems is interesting for the scientific community, as well as for policy makers and entrepreneurs (König et al., 2018).

Finding appropriate fish-plant combinations adapted to local conditions without compromising yields is one of AP’s key challenges (Knaus and Palm, 2017; Suhl et al., 2016). Although the potential fish-plant combinations are quite high, the main fish and plant crops being used are tilapia and herbs. In contrast to the main freshly consumed fish species in Europe (salmon, cod, hake and mackerel), today's AP systems produce mainly tilapia (27%), followed by catfish (10%), ornamental fish (8%), and trout (7%) (Villarroel et al., 2016). Love et al. (2014) also pointed out tilapia as being the fish most commonly raised in AP systems in the US. However, a consultant interviewed in König et al. (2018) stated, referring to AP, that “to be considered for organic certification, fish stocking rates needed to be diminished. This would require high quality, specialty fish, not tilapia, for generating sufficient income”. Hence, ornamental fish could be considered as a good alternative given that they attain a much higher price in the market.

On the other hand, a diverse range of vegetable crops is grown in Europe's AP facilities, with herbs (58%, including basil), lettuce (47%, including salad greens) and tomatoes

(32%) being the major crops (Villarroel et al., 2016). Lettuce was precisely suggested by Rakocy (2012) as a good crop for AP production due to its short production period of three to four weeks and as a consequence of a relatively low pest pressure.

AP systems can be used with a commercial purpose, but they are also becoming a medium with great potential for contributing to family self-consumption and food sovereignty, conveyed through small-scale and low-cost systems that can be adapted to many locations. They are particularly interesting in urban environments with reduced space for food production (e.g., roofs of buildings, urban vegetable gardens, backyards). In these cases, the biggest constraint is the size of the AP facility. Maucieri et al. (2018) consider small installations those between 50-200 m^2, very small between 5-50 m^2 and micro systems < 5 m^2. In spite of this classification, we considered as small-scale aquaponic systems (SAS) those with a total covered area under 20 m^2.

Several types of SAS are proposed (Maucieri et al., 2017b; Menon, 2013; Somerville et al., 2014), their main difference being the hydroponic sub-system utilised. The most commonly used are the media-based grow bed, the Deep Water Culture (DWC) or the floating raft system, and the Nutrient Film Technique (NFT). The media-based grow bed is a hydroponic trough filled with inert substrate (e.g., expanded clay, perlite, pumice, gravel), serving as root support and microbial substrate. The water is commonly supplied in an ebb and flow pattern, ensuring sequential nutrition and aeration. The DWC system consists of large troughs with perforated floating rafts, where net plant pots are inserted so that the roots are continually submerged in the water tank. The NFT system uses narrow channels of perforated squared pipes where the roots are partially immersed in a thin layer of streaming water (Goddek et al., 2015).

In a study about commercial AP systems in the US (Love et al., 2014), the most commonly used hydroponic sub-systems are floating rafts and media beds while the NFT and vertical-like systems are much less widespread.

It is very important to determine which are the most appropriate systems for certain conditions, but more work should be done to assess the options and compare their performance. In fact, Maucieri et al. (2017) reviewed more than 120 publications on AP of the last 30 years and only 9% of them compared different types of hydroponic sub-systems. The increasing interest in SAS, especially in developing countries and even in urban agriculture surroundings, led FAO to the publication of a remarkable document (Somerville et al., 2014) that can be used as a handbook to understand, build and manage SAS using common materials easily found at any location.

Then, the main objective of this work is the comparison in terms of fish and crop production and water consumption between three different SAS based on modified FAO's models using as a case study a joint production of lettuce (*Lactuca sativa* L.) and goldfish (*Carassius auratus*).

2. Materials and methods

2.1. Aquaponic systems' description and experimental setup

The SAS were installed in a 65 m^2 greenhouse located at the School of Agricultural Engineering (University of Seville, Seville, Spain; 37°21'6.45" N, 5°56'12.35" W). Three different systems designed according to FAO´s SAS (Somerville et al., 2014) were tested. The fishes were contained in prismatic (1.14 m x 1.2 m x 1 m) intermediate bulk containers (IBC) which served as tanks (one for each SAS) filled with 1 m^3 of water. They were wrapped in a black mesh to avoid algae proliferation inside. Water was aerated using a 400 $L \cdot h^{-1}$ air pump (Air pump 400, Eheim, Germany) for ensuring a correct level of oxygen dissolved in the water for the fishes. In order to daily replenish the water in the SAS, another 2 m^3 cylindrical tank was used to previously store water and favour chlorine evaporation.

The first SAS (SAS1) was built according to original FAO guidelines. It used an NFT system composed of five 3 m long PVC pipes with a diameter of 0.11 m, separated 0.11 m from each other. They were placed on concrete blocks levelled to obtain a slope of 1 %. Each pipe had 12 holes (0.05 m of diameter) separated 0.25 m from each other. Two smaller 0.21 m^3 cylindrical tanks 0.93 m high and 0.58 m of diameter) were used for the mechanical filter (or clarifier) and the biofilter. The mechanical filter concentrates solids at the centre and bottom of the tank due to the tea leaf paradox phenomenon. For the biofilter, the tank was filled with 1000 standard and 600 handmade bioballs, small, pegged plastic balls used as the biological media. These bioballs are intended to maximise the flow of air and water, avoiding retention of liquid and providing greater surface living area for beneficial bacterial to thrive. As a result, they provide both efficient mechanical (they do not clog easily) and biological filtration and efficiently reduce ammonia and nitrite. These handmade bioballs were manufactured from small pieces of corrugated PVC pipes 0.03 m in diameter, one inserted into the other. Water passed from the fish tank to the mechanical filter and afterwards to the biofilter by gravity. A water pump (Compact+ 5000, Eheim, Germany) with an adjustable flow between 2500-5000 $L \cdot h^{-1}$ was used for sending 80 % of the water from the biofilter back to the fish tank and the remaining 20 % of the water to the NFT pipes. Inside them, the water reached a depth of approximately 0.01 m and was again recovered at the end of the NFT pipes in order to be conducted back to the biofilter (Figure 1).

The second system tested (SAS2) used a floating raft as a hydroponic subsystem. In order to avoid the accumulation of solids in the media bed used as biofilter, original FAO model was modified introducing a clarifier that reduced the amount of solids at the bottom of the media bed and contributed to elude anaerobic conditions. Water was conducted by gravity from the fish tank to a clarifier (exactly equal to the one described in SAS1) and from there to a 0.48 m^3 tank (1 m x 1.2 m x 0.4 m) filled with 360 L of pre-washed expanded clay that acted as a biofilter. Afterwards, the water passed to a sump tank with a capacity for 0.54 m^3 (1 m x 1.2 m x 0.45 m). An Eheim Compact+ 5000 pump sent 80 % of the water back to the fish tank and the remaining 20 % to two identical raft tanks of 0.48 m^3. The floating rafts were made with 0.04 m thick extruded polystyrene foam (XPS) sheets (1 m x 1.2 m) with holes (0.06 m of diameter) to place the plants separated 0.25 m from each other. The biofilter was provided with a bell syphon which favours the aeration of media particles by continuously filling and emptying the tanks (Fox et al., 2010). Additional aeration was provided in the fish and raft tanks by means of an air compressor (model ACQ-903, BOYU, Raoping Guangdong, China).

The third system (SAS3) had the same components as SAS1 with the exception of the NFT system which was replaced by a vertical felt living wall system mounted on a galvanised stainless steel structure 2.4 m high x 2 m wide and at an angle of 20º with respect to the vertical plane. The vertical felt was composed by four modules (0.75 m x 1 m), two in the upper position and two below. These modules had two layers, the outer one was made of a porous material to favour the aeration of the roots and the inner one was a geotextile layer which helped to distribute the water. Both layers were sewn together forming a 0.2 m x 0.25 m grid of pockets filled with expanded clay in which plants were inserted. Expanded clay was chosen in order to favour a better aeration of the root zone, given that the vertical felt was intended to be receiving water at all times. Though the felt living wall has a maximum capacity of 20 plants·m^{-2}, not all the pockets were used in order to have an equivalent planting density to the other SAS, also according to the fish stock.

As a control (Ctrl), 20 pots were filled with perlite and daily irrigated with 0.2 L per pot of a Hoagland nutrient solution.

Two tests were performed, the first one from May 9th 2016 to June 22nd 2016 (44 d) and the second, from November 8th 2016 to January 11th 2017 (54 d).

2.2. Fish and plant species

Goldfish (*Carassius auratus*) was the fish species selected due to its adaptability, especially in terms of water temperature (from 0 to 35 ºC, with an optimum of 18-24 ºC) (Watson et al., 2004). Goldfish also have, as ornamental fishes, a higher value than other species commonly used in AP. In addition, goldfish are omnivorous, so they do not need so much animal origin protein, which makes their diet more sustainable (Sealey et al., 1998). For this study, 160 specimens with an average weight of 30 g per fish and aged between 2 and 4 months were acquired from a specialised store. For the first test, they were distributed among the three SAS tanks in order to have a similar stocking density (1.6 kg m^{-3}). After the first test, all the fishes were moved outside the greenhouse to a shaded artificial pond where they were kept during the summer months to avoid excessive heat. For the second tests, the fishes were bigger, having an initial average weight of 53.3 g per fish and they were again distributed with the aim of obtaining a similar total fish weight in each tank (2.5 kg m^{-3}).

Three different types of lettuce (*Lactuca sativa* L.) were used, Lollo rosso (LR) and Lollo bionda (LB) in the first test, and romaine lettuce (RL) in the second. The plants were previously pre-cultivated in seedbed trays for 21 days. In the first test, 20 plants (10 LR and 10 LB) were transplanted to each SAS two weeks after putting the fishes in the tanks in order to already have a sufficient concentration of nutrients for the seedlings. In the second test, 24 plants were transplanted in each system one week after putting in the fishes. The difference in the number of plants used per SAS and in the moment of the transplant is due to the higher size of the fishes in the second test.

2.3. System operations and measurements performed

At the beginning of each test, all the SAS were subjected to a period of four weeks without fishes or plants in order to allow the proliferation of nitrifying bacteria. Also living bacteria (Biodigest Pro, Probidio, Marseille, France) and ammonia were artificially introduced in the tanks to speed up the process.

AP systems usually show low concentration levels of elements such as K, Fe or Ca. (Graber and Junge, 2009). Therefore, the plants were periodically examined to observe the occurrence of nutrients insufficiency. To alleviate these potential deficits, K_2SO_4 at 1.5 % was foliarly applied in all SAS. The applications were performed twice a week (Mondays and Fridays), first thing in the morning with a manual sprayer. Chelated iron solution (1%) was directly added to the water (EDDHA Sequestrene 138 Fe), 0.1 L in the case of SAS1 and SAS3 and 0.14 L in SAS2 (due to its higher volume of circling water). This was done on Fridays every fortnight.

Fishes were fed twice a day using pond sticks (Prodac International S.r.l, Cittadella, Italy) mixed food with 24.4 % of protein. The daily quantity of food was calculated as 1 % of the total fish weight at the beginning of the tests and was gradually incremented every fortnight up to 2 % of the total weigh. In the first test, a total of 742 g was used in each SAS with a daily amount varying between 15 and 24 $g \cdot d^{-1}$. In the second test, 3247 g were fed to the fishes of each SAS, with daily amounts between 24 and 65 $g \cdot d^{-1}$.

Water parameters were monitored during both tests. Maximum (T_{max}) and minimum (T_{min}) daily values for water temperature were registered inside the fish tank in each SAS by means of a maximum-minimum thermometer (TFA, Germany). Water samples were collected periodically in order to measure pH, electrical conductivity (EC) and nitrates. The pH and EC were determined with a pH-meter GLP 22 and an EC-Meter BASIC 30 (Crimson instruments, Barcelona, Spain); respectively. Nitrates concentration was obtained by means of an RQflex 10 plus (MERK, Darmstadt, Germany). Also, the water consumption was measured daily in order to calculate the average daily consumption (DWC) for each SAS, the total volume of water (TWC) used in each test and the water replenishment rate (WR). The latter was estimated as the ratio between the DWC and the total water running in each SAS. The water used for replenishment had a pH of 7.9 and an EC of 263 $\mu s \cdot cm^{-1}$.

During the tests, plant development evolution was observed by weekly registering the number of leaves, height and shoot diameter for each plant. At the end of each trial all the plants of the three SAS were harvested, separating the foliage from the root system in order to properly work with their aerial part (Bailey and Ferrarezi, 2017). The fresh weight per plant (FWP) and the total fresh weight (TFW) were determined for each SAS considering only the shoots, not the roots. Afterwards, the shoots were dried in an oven at 65 ºC during 48 hours in order to obtain the dry weight per plant (DWP), and the dry matter content (DMC), calculated as the ratio between the DWP and the FWP. This was done per plant for the first test but not for the second. So, in test 2 average values for the FWP, the DWP and the DMC were calculated from the TFW, the total dry weight and the number of plants.

The fishes were counted and weighted every fortnight in the first test and every three weeks in the second. Different indicators were used in order to monitor and compare the fish populations. Both the total (TW) and the average weight per fish (AWF) were obtained. For relative fish growth, the specific growth rate (SGR) is normally accepted as the standard measure. Yet, Lugert et al. (2016) described the SGR as mathematically unsuitable and recommended using the absolute growth rate (AGR). As a result, both the SGR and the AGR were calculated as follows:

$$SGR\ (\mathrm{g}\cdot\mathrm{day}^{-1}) = \frac{\ln AWF_t - \ln AWF_{t-1}}{\Delta t} \qquad (1)$$

$$AGR\ (\mathrm{g}\cdot\mathrm{day}^{-1}) = \frac{AWF_t - AWF_{t-1}}{\Delta t} \qquad (2)$$

where: AWF_t and AWF_{t-1} are the AWF in to different times and Δt represents the number of days from one measurement to the other.

A feed conversion ratio (FCR) is used to assess the efficiency with which the fishes convert the feed into body weight. This was calculated as:

$$FCR\ (\%) = \frac{FI}{TW_f - TW_0} \qquad (3)$$

where: FI is the feed intake (g) and TW_f and TW_0 are the TW at the end and the beginning of each test respectively.

Finally, the survival rate (SVR) was calculated as the ratio between the initial and the final number of fishes in each SAS.

2.4. Statistical analysis

Statistical analyses of the data were performed with the SPSS 24 statistical package. For statistical comparison, a one-way ANOVA was used. The normality of the data was assessed by means of the Shapiro-Wilk test. When data were not normally distributed, a nonparametric ANOVA (Kruskal-Wallis test) was used to confirm significant differences. Post hoc analysis was performed using the HSD Tukey test and the Games-Howell test (when variances were not equal). Differences were considered significant when $P < 0.05$.

3. Results

3.1. Water

The observed values for water temperatures, pH and EC varied in the range of 10-34 ºC, 6-8.4 and 230-481 $\mu s \cdot cm^{-1}$ respectively, being within the adequate levels for the correct operation of AP systems. No big differences were observed among the SAS in these parameters. Nevertheless, the T_{max} was slightly higher in SAS1 during both tests due to the higher temperature achieved in the NFT pipes under direct sun light. The EC increased between 30 and 60 % in test 1, depending on the SAS. In the second test, the increments were higher (63-84 %). The nitrate concentration was usually higher in SAS1, SAS2 being the one that presented lower values, probably due to its higher water volume.

The SAS showed substantial variations according to the water required for their operation. SAS2 was the system with lower consumption (15.1 $L \cdot day^{-1}$) in the first test, while SAS1 consumed less water in the second (13.3 $L \cdot day^{-1}$). In both tests, SAS3 showed the worst values, requiring 1.5 times more water than SAS2 in test 1 and 2.4 times more than SAS1 in test 2. Some differences in water consumption were observed between tests 1 and 2. In SAS1, a 38 % reduction in the DWC was observed in the second test, leading to an improvement in the WR, while the WR increased considerably in SAS3. SAS2 showed a similar DWC in both tests.

3.2. Lettuce production

Crop development was monitored from the transplant until the harvest. Tables 2 and 3 show the mean values of the plants characteristics (number of leaves, height and diameter of the shoot) at the moment of the harvest for the first and second test respectively. In both tests, SAS1 and Ctrl showed the best results, which were not significantly different in any of the characteristics. In the 1st test, lettuces in SAS2 had more leaves than in SAS3 but the height and diameter of the plants were similar. In the 2nd test, SAS2 had no significant differences with SAS1 and Ctrl in the number of leaves. Notwithstanding, plants in SAS2 had a different size than the rest of the systems. SAS3 showed the worst performance in both tests.

Looking into the evolution of these parameters during the crop cycle (Figure 2), similar conclusions can be reached. Yet, it is interesting to highlight that both in LB and LR SAS1 showed a slightly higher precocity than Ctrl. With RL, it was the opposite case. LB and LR showed a poor evolution in SAS2 and SAS3 even decreasing the achieved size in the second period of the crop cycle. This decrease happened again in the case of RL for SAS2 though the crop recovered. SAS3 also performed poorly with RL. Figure 3 shows photographs of the result obtained for each of the SAS in both tests.

In terms of production, Tables 4 and 5 show the values for the TFW (g) and averages for the FWP (g), the DWP (g) and the DMC (%) for test 1 and 2 respectively. Lettuce TFW was similar in test 1 for SAS1 and Ctrl, with no significant differences in the FWP, the DWP and the DMC. In the second test the TFW and the FWP were considerably higher in SAS1, which produced 43 % more than Ctrl. Nonetheless, the DWP was similar between both and the DMC was higher in Ctrl. SAS2 produced 6.7 and 4.1 times less than SAS1 in test 1 and 2, respectively. SAS3 exhibited the worst values of all indicators in both tests with the exception of the DMC in test 2 which was very high (due to the low water content in the fresh leaves).

In terms of the productivity per area unit, the values were 0.49, 0.09, 0.02 and 1.24 $kg \cdot m^2$ for SAS1, SAS2, SAS3 and Ctrl respectively in test 1. In the case of the second test, 3.38, 0.98, 0.24 and 2.84 $kg \cdot m^2$ were obtained for SAS1, SAS2, SAS3 and Ctrl respectively. Looking into the productivity per fish food, the input values were 1.59, 0.24 and 0.03 kg of lettuce·kg fish food^{-1} in test 1 and 0.36, 0.05 and 0.01 kg of lettuce·kg fish food^{-1} in test 2 for SAS1, SAS2 and SAS3 respectively.

3.3. Fish production

Table 6 shows the parameters of fish production calculated in both tests. During the first test, the best increment in the TW (258 g) was found in SAS3 and the worst (97 g) in SAS2, SAS1 showing an intermediate value. The ΔTW was similar for all the SAS in the second test, though a bit higher in SAS2. The AWF at the beginning of test 1 was around 30 g, finishing with an average of 35 g. In the second, the AWF changed from 53 g in average to 74 g. The SGR values ranged from 0.19 (SAS2) to 0.56 (SAS3) in test 1 and were between 0.37 and 0.41 in the second. The FCR was between 3 and 4 %, except for the case of SAS2 in test 1 (7.6 %). Fish survival was very good (over 90 %) in all cases. Fishes even reproduced in test 2 (SAS1 and SAS2).

4. Discussion

In this study, three different AP systems are tested in order to assess their performance for a small-scale production. The main difference between them can be found in the hydroponic sub-system employed. But it is not easy to determine which one is best suited to integration with recirculating fish culture (Lennard and Leonard, 2006).

Regarding lettuce production, both SAS1 and Ctrl had similar results in the first test, though the latter showed more than the double productivity per area unit (1.24 $kg \cdot m^2$)

than SAS1 (0.49 kg·m^2). This is due to the higher plant density of Ctrl. However, in test 2, the good outcome in production obtained in SAS1 resulted in a higher productivity (3.38 kg·m^2) than Ctrl in spite of the difference in planting density. Obviously, if the planting density in the SAS is increased (a higher amount of fishes would also be required), these results in productivity would improve.

When comparing the results obtained in this study with those reported by other authors (Table 7), it can be concluded that SAS1 performed very well in both types of lettuce. SAS2 showed poor productivity for LB and LR compared to that obtained by Maucieri et al. (2018) (0.4 kg·m^2) in a micro AP floating raft system with *Lactuca sativa* cv. *Bionda Ricciolina di Trieste* more similar to LR and LB. The same can be said for RL, given that the productivity obtained in SAS2 was 0.98 kg·m^2 and Seawright et al. (1998) reported 2 kg·m^2 when producing a romaine lettuce cultivar (*Jericho*) also in floating rafts. No system similar to SAS3 was found in the literature reviewed.

The production per unit area (kg·m^{-2}) is a useful indicator to be able to compare productivities in different systems. But this indicator can be tricky in AP systems as it is normally calculated taking into account the actual cropping area used for the plant production. Still, in order to be more accurate, in AP the surface needed for AP production of crops should take into account the space required for the fish tank, the biofilters, etc. In the same line, to determine the fish culture productivity, the volume of the fish tank is usually taken into account, but not the total volume of water employed in the process. Consequently, establishing proper comparisons with the results obtained in other studies is not easy without knowing the exact boundary conditions for the calculation of the indicators.

It is not clear if the productivity in AP is higher than in hydroponics. It will depend on the type of lettuce and on the particular conditions in which it is produced. For instance, Nozzi et al. (2018) performed a study in floating rafts with a different quantity of supplement of nutrients. They obtained a production between 4 and 6.13 $kg{\cdot}m^{-2}$ vs. 5.65 $kg{\cdot}m^{-2}$ in hydroponics. Average shoot weight ranged from 222 to 340 g, being 313 g in hydroponics. Delaide et al. (2016) did not observe significant differences when growing lettuce in two identical trials both in an NFT AP system with tilapia (80.55 and 35.72 $g{\cdot}plant^{-1}$) and a hydroponic system (98.17 and 39.64 $g{\cdot}plant^{-1}$). Johnson et al. (2017) reported a yield of 0.258 $kg{\cdot}m^{-2}$ for a Lollo cultivar production in a grow bed, finding a significant difference with the same crop in pure hydroponic production (0.47 $kg{\cdot}m^{-2}$). But the difference was not significant for romaine lettuce (0.53 $kg{\cdot}m^{-2}$ compared to 0.49 $kg{\cdot}m^{-2}$ in hydroponic).

Big differences have been observed between Lollo and romaine lettuce. The latter turned out to work better in all the SAS tested. Although LB's performance seemed to be better than LR's, differences between them both in terms of characteristics and production were not statistically significant. Johnson et al. (2017) also found that green leaf lettuce (*Butterhead*, *Bibb* and *Lollo*) had a higher average yield compared to red cultivars within the same subtypes.

Curiously, unlike crop production results, in terms of fish production, SAS3 worked slightly better than the other SAS. That might be due to the better water quality given that the water tank was replenished more frequently. The FCR ranged between 2.88 and 7.65, common values for *Carassius auratus*. Sarkar and Upadhyay (2012) observed values in the range of 1.5-4.18 in goldfish production subjected to different photoperiodic regimes. In a study using fed diets with different digestible protein and energy levels (Bandyopadhyay et al., 2005), the FCR for goldfish was between 1.94 and 2.61. The range of values was wider (3.74-13.06) in Souto et al. (2013). Shete et al. (2013) obtained FCR values from 4.5 to 4.8 in an AP system combined with spinach with varied water circulation periods. Nonetheless, SGR values observed (ranging in our study between 0.19 and 0.56) were low compared to those obtained by Sarkar and Upadhyay (2012) and Bandyopadhyay et al. (2005) (1.02-2.85 and 1.56-2.13, respectively). Shete et al. (2013) also obtained SGR values from 1.30 to 1.44, though they started with much smaller fishes. Only Souto et al. (2013) showed similar values (0.15-0.45) to our results.

Apart from obtaining a fair production of crops and fishes, water consumption must be another factor to take into account in order to determine the sustainability of AP systems. The quantity of water required in the process is directly influenced by the hydroponic component of an AP system due to direct evaporation and plant evapotranspiration (Maucieri et al., 2017a). In our study, differences in water consumption were considerable among the SAS. In this sense, the management of the AP facilities is also very important. In fact, there are variations in water consumption in the same SAS between both tests. Obviously, as the tests were carried out on different dates, environmental conditions (especially the temperature) affected the water loss due to evaporation. Also, different varieties of lettuce and number of plants were employed. Notwithstanding, in SAS2 and SAS3, the TWC was higher in the second test (even though the opposite was expected) due to some problems in the management. On the contrary, the TWC was considerably reduced in SAS1. This could be caused because the NFT pipes reached high temperatures in the first test, increasing evaporation. Higher values of water consumption were observed in SAS3, due to the direct evaporation from the vertical felt. In the second test, algae proliferation on the felt also increased water consumption and, on the other hand, forced part of the water to be spilled out of the system. In spite of those differences in water consumption, all the WR values were between 0.76 and 2.48, which are in the lower part of the 0.5-10 % range observed in AP (Love et al., 2015b).

Then, the question in mind is how much water is needed to produce a kg of lettuce? As a general value, Mekonnen and Hoekstra (2011) suggested that the average water footprint for conventional lettuce production was 237 $L \cdot kg^{-1}$. A similar number (250 $L \cdot kg^{-1}$) was proposed by Barbosa et al. (2015), though for hydroponics the value was much lower (20 $L \cdot kg^{-1}$). However, fish production should also be taken into account in AP. Then, Delaide et al. (2017) considered that the water needs can be split 50/50 for crop and fish production. Following that assumption, the water footprints for lettuce production in our study were 41 (SAS1), 196 (SAS2) and 2446 $L \cdot kg^{-1}$ (SAS3) for RL, therefore being very good in the NFT sub-system. Other authors reported values between 100 and 250 $L \cdot kg^{-1}$ (Delaide et al., 2017; Love et al., 2015a). For LB and LR, it took ten times more water to produce 1 kg of crop in SAS1 (413 $L \cdot kg^{-1}$). For SAS2 and SAS3 the water footprint was exorbitant (1950 and 25200 $L \cdot kg^{-1}$ respectively). Taking the differential fish growth during the crop cycle also into account, the total water footprint in the best case scenario (SAS1 in test 2) was 72.9 $L \cdot kg$ of produce^{-1}.

In their review, Maucieri et al. (2017) determined that several authors found the NFT system to be less efficient in terms of nitrates removal and crop yield. In our experiment that was true for the former but not for the latter. They explained the lower nitrates removal capacity as being due to the restricted contact between the roots and the water in the NFT system. In medium-based and floating hydroponic systems plants have their entire roots in contact with the water, providing them with more surface area to assimilate nitrate. Nevertheless, this is not totally true for the case of SAS3 and, even then, lower levels of nitrates were also observed in it. Probably, the reduction in nitrate levels in this system is due to the high amount of water consumption caused by leaks in the felt, as described above.

Lennard and Leonard (2006) found, in a 21-day experiment with Murray cod (*Maccullochella peelii*) and Green Oak lettuce, the highest production in a gravel bed system, followed by floating rafts, the NFT system being the least productive. Unlike in our study, they did not observe any effect of the hydroponic system on fish growth. They measured significantly higher nitrate concentrations in the NFT system, corroborating our results.

The better results obtained in the NFT could be due to the fact that water temperature was higher than in other SAS, which favoured the nitrification process, with optimum values between 25-30 ºC (Delong and Losordo, 2012). Water temperature could also affect the improvement of the nutrients uptake by the plants and favour a certain precocity as observed in SAS1 (Moorby and Graves, 1980). SAS2's lesser crop production could be explained by a deficient aeration of the root zone (Zeroni et al., 1983). In our study, concentration of dissolved oxygen in SAS2 was enough for fish growth but probably suboptimal for plants development. However, this could be easily solved just replacing the air pump used by a more efficient blower and increasing the number of air stones in the hydroponic trays.

Undoubtedly, SAS3 had the worst performance. Even when this kind of systems has shown a very good result for living walls with ornamental plants, it seems that it does not perform so well for food production species such as lettuce. This can be caused by a lower radiation influx due to the vertical wall (even when it had a slight slope). Also, water was distributed through the felt but the expanded clay inside the pockets did not receive enough water and nutrients (this effect was favoured by the slope). In living walls, plants are expected to be there for a long time, so roots end up anchoring to the felt and thus obtaining water from it. Also, if other substrates with more capillarity than expanded clay had been used, such as perlite, this could have improved the results. For instance, an AP system comprised of a pond with ornamental fishes in conjunction with a living wall has been tested in the School of Agricultural Engineering (Universidad de Sevilla, Seville, Spain). In it, perlite is employed as the substrate inserted in the pockets, having very good results (not published) regarding plant development.

Another problem observed in this SAS was algae proliferation on the felt due to the perfect conditions generated for it (humid environment, high level of nutrients and enough lighting). This caused competition with the crop and higher water consumption, apart from other problems such as obstruction of irrigation emitters, water derived from outside the system and more hours required for maintaining the systems. The aim of this SAS was to minimise the space that it took up, maximising the production per area unit. After this study, we still find it desirable to develop a SAS that can be placed in a reduced space, so improvements to the vertical system employed (e.g., suppressing the slope, using NFT pipes instead of the felt, etc.) are needed. However, other systems must be tested to find better solutions.

SAS1 could be considered a good system to improve crops precocity during cold seasons, due to the ability of NFT pipes to maximize water heating using sunlight. However, it is recommended the use of plants with limited root system development, as they could compromise correct water flow through the channels, increasing water level and thus reducing aeration. On the contrary, production along warm seasons could be improved with the use of white or metalized NFT pipes, in order to avoid excessive water heating.

Productivity of SAS2 could be incremented by enhancing the efficiency of water aeration with additional air stones or more powerful blowers. This system has some extra advantages associated to its higher water volume that improves its thermal and chemical inertia. Due to the huge volume of hydroponic trays, it is a recommendable system for the production of plants with large root systems.

SAS can be considered as a good option for self-supply of fresh vegetables and fishes and if they are used with some higher value species (such as goldfish), they can also serve as a potential income for family economies. In order to promote the use of SAS for self-production, especially in the case of non- skilled users with a low knowledge of this type of agricultural systems, it is very important to simplify the systems' management. To do so, automation plays an essential role. As a result, developing simple and affordable automation systems that allow the simplification of tasks involved in the management of SAS is sought.

Reused, not expensive materials should be used for the construction of the SAS for it to be economically sustainable. In the case of this study, each SAS cost around 1,000 €. However, the most significant expenses are related with the management of the systems, mainly inputs (i.e., water and energy) and personnel costs. In this sense, if the SAS is self-managed and the installation is designed to simplify and optimise the management tasks to minimise the labour hours, these personnel costs could be disregarded.

Also, optimising water and energy use would be a measure for reducing costs and, at the same time, making the AP production more sustainable. Simple strategies can be developed in order to achieve these reductions of inputs. As an example, Silva et al. (2018) used a dynamic root floating technique for natural aeration, in order to achieve a 11.4 % reduction in electric power consumption. In the same line, Fang et al. (2017) also improved the system's energy efficiency by 77 % through reducing aeration intensity. Maucieri et al. (2018) also suggest that more research should be focused on reducing energy inputs as electricity was shown to be the most important factor in the life cycle analysis that they performed.

5. Conclusions

This study presents a comparison between three small-scale AP systems whose main difference was the hydroponic subsystem employed. The NFT outperformed the rest, both in terms of crop production and water consumption. Lettuce production in it was similar or even better than in the hydroponic control. No big differences were found in the fish production between systems.

There is still a long way to go to totally develop AP systems. Though their potential is clear, there are still some gaps that hinder the development of productive models that are fully integrated within the framework of a circular economy, and which must be resolved in order to achieve a production system that is simple to use, environmentally friendly, generates little or no waste and is even capable of reusing waste produced by other external systems. In this respect, additional efforts are needed to work on subjects, such as determining the most interesting plant-fish binomials for different locations, improving the efficiency in the use of water energy, using alternative / renewable sources and optimising the resources' consumption, developing automatisms that facilitate the management of the systems, and multi-criteria systems to support decision making for their management or formulating feeds for fishes when the use of raw materials from extractive fisheries (fish meal and fats) is reduced.

SAS are particularly interesting for self-production and even more so in urban environments with reduced available space. The impact of this type of production on society in terms of social cohesion, self-employment, empowerment, improvement of eating habits, etc., should be also taken into account.

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FIGURES

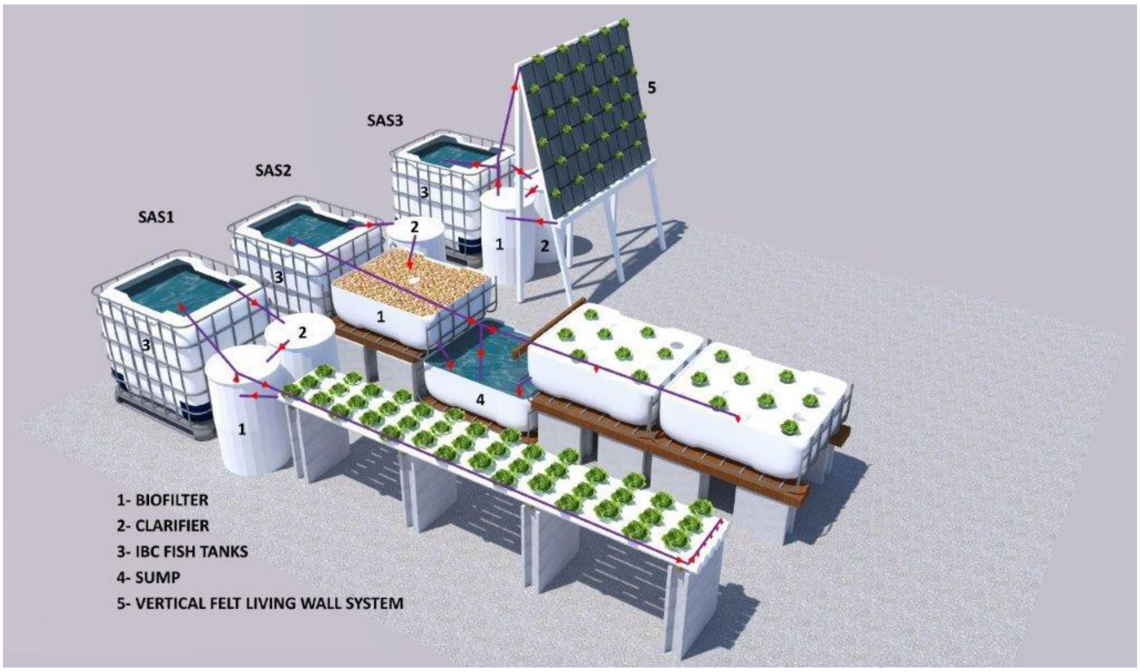

Figure 1. Experimental layout and SAS schematics. Red arrows indicate the water direction

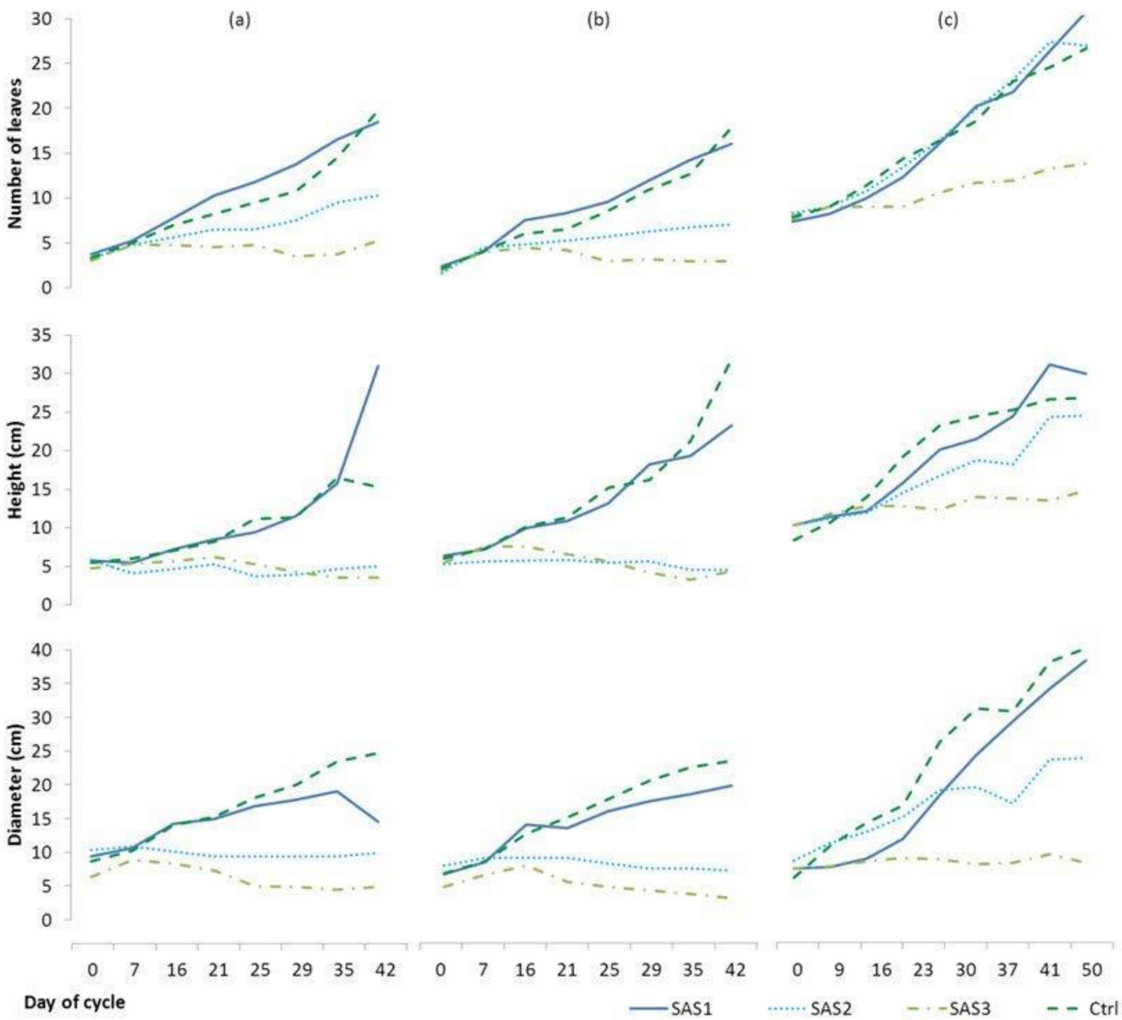

Figure 2. Evolution of average number of leaves, height and diameter of LB (a), LR (b) and RL (c).

Figure 3. Photographs of the crop prior to harvest in SAS1 (a, d), SAS2 (b, e) and SAS3 (c, f) in the first (a-c) and second test (d- f).

TABLES

Table 1. Water parameters in both tests for all the SAS

	1st test			2nd test		
	SAS1	SAS2	SAS3	SAS1	SAS2	SAS3
T_{max} (ºC)	27.0 ± 2.5	25.6 ± 2.9	25.6 ± 3.1	23.0 ± 2.2	20.4 ± 3.4	19.4 ± 2.0
T_{min} (ºC)	23.0 ± 3.6	21.2 ± 2.2	21.0 ± 2.8	16.8 ± 0.8	17.3 ± 1.4	16.3 ± 2.7
pH	7.9 ± 0.2	8.1 ± 0.2	8.1 ± 0.1	7.0 ± 0.6	7.7 ± 0.4	7.6 ± 0.4
EC ($\mu s \cdot cm^{-1}$)	329 ± 55	309 ± 33	320 ± 57	370 ± 58	366 ± 55	378 ± 59
Initial value	285	274	256	271	246	268
Final value	392	357	406	481	455	438
NO_3^- (ppm)	38.6 ± 21.3	22.2 ± 08.7	26.8 ± 10.7	62.7 ± 19.8	36.8 ± 12.9	39.4 ± 16.3
DWC ($L \cdot day^{-1}$)	21.6	15.1	23.3	13.3	15.4	32.2
TWC (L)	972.0	680.0	1048.4	666.9	770.9	1609.9
WR (%)	1.66	0.76	1.79	1.03	0.77	2.48

Table 2. Mean values (± SE) of number of leaves, height (cm) and diameter (cm) prior to harvest in the 1st test. Means with the same letter in each column are not significantly different at the $p < 0.05$ level according to the HSD Tukey test ([1], [3]) and the Games-Howell test ([2]).

	Leaves [1]	Height [2]	Diameter [3]
SAS1	17.2 ± 1.1a	23.7 ± 3.5a	17.2 ± 2.3b
SAS2	8.7 ± 1.0b	4.2 ± 0.5b	8.7 ± 0.8c
SAS3	4.2 ± 0.7c	3.4 ± 0.3b	4.2 ± 0.6c
Ctrl	18.7 ± 1.2a	18.9 ± 2.5a	24.1 ± 1.1a

[1] χ^2 *=44.644;* [2] χ^2 *=24.046;* [3] χ^2 *=23.612; d.f.=3, P=0.000*

Table 3. Mean values (± SE) of number of leaves, height (cm) and diameter (cm) prior to harvest in the 2nd test. Means with the same letter in each column are not significantly different at the $p < 0.05$ level according to the HSD Tukey test.

	Leaves [1]	Height [2]	Diameter [3]
SAS1	30.4 ± 1.7a	33.9 ± 1.1a	38.0 ± 1.8a
SAS2	26.7 ± 1.4a	27.8 ± 0.9b	23.8 ± 1.4b
SAS3	13.9 ± 1.8b	17.0 ± 1.4c	8.7 ± 0.9c
Ctrl	26.4 ± 0.9a	30.4 ± 1.1ab	39.7 ± 1.5a

[1] χ^2 *=21.944;* [2] χ^2 *=27.382;* [3] χ^2 *=32.394; d.f.=3, P=0.000*

Table 4. TFW (g) and mean values (± SE) for FWP (g), DWP (g) and DMC (%) in the 1st test. The same letter in each column denotes not significant differences at the $p < 0.05$ level according to the Games-Howell test.

	TFW	FWP[1]	DWP[2]	DMC[3]
SAS1	1176.2	58.8 ± 6.3a	7.20 ± 1.33a	13.0 ± 2.2a
SAS2	174.4	8.7 ± 1.3b	0.81 ± 0.09b	11.3 ± 0.9a
SAS3	20.8	1.1 ± 0.2c	0.07 ± 0.03c	4.5 ± 1.5b
Ctrl	1489.2	74.4 ± 2.9a	6.63 ± 0.34a	8.9 ± 0.3a

[1] χ^2 *=65.360;* [2] χ^2 *=65.421;* [3] χ^2 *=14.758; d.f.=3, P=0.000 (0.002 in* [3]*)*

Table 5. TFW (g) and average values for FWP (g), DWP (g) and DMC (%) in the 2nd test.

	TFW	FWP	DWP	DMC
SAS1	8109.9	337.9	19.0	5.6
SAS2	1966.5	81.9	5.2	6.4
SAS3	329.1	13.7	1.6	11.4
Ctrl	5681.5	236.7	18.0	7.6

Table 6. TW, increment in total weight (ΔTW), AWF, SGR, AGR, FCR and SVR. $_0$ and $_f$ subscripts denote that the indicator refers to the beginning and end of each test, respectively.

	1st test			2nd test		
	SAS1	SAS2	SAS3	SAS1	SAS2	SAS3
TW_0 (g)	1620	1624	1603	2457	2482	2457
TW_f (g)	1811	1721	1861	3497	3583	3443
ΔTW (g)	191	97	258	1040	1101	986
AWF_0 ($g \cdot fish^{-1}$)	30.0	30.6	30.2	51.2	56.4	52.3
AWF_f ($g \cdot fish^{-1}$)	34.8	33.1	38.0	69.9	79.6	73.3
SGR ($g \cdot day^{-1}$)	0.36	0.19	0.56	0.37	0.41	0.40
AGR ($g \cdot day^{-1}$)	0.12	0.06	0.19	0.22	0.28	0.25
FCR (%)	3.88	7.65	2.88	3.12	2.95	3.29
SVR (%)	96	98	92	104	102	100

Table 7. FWP and productivities for several lettuce cultivars in various AP systems obtained by different authors

AP system	Lettuce cultivar	FWP (g)	Productivity ($kg \cdot m^{-2}$)	Author
Floating raft	Green Oak Leaf	-	4.47	Lennard and Leonard (2006)
Floating raft	Jericho	-	2.00	Seawright et al. (1998)
Floating raft	Bionda Ricciolina di Trieste	-	0.4	Maucieri et al. (2018)
Floating raft	Salanova	222-340	4-6.13	Nozzi et al. (2018)
Grow bed	Green Oak Leaf	-	5.05	Lennard and Leonard (2006)
Grow bed	Lollo	-	0.26	Johnson et al. (2017)
Grow bed	Romaine[1]	-	0.53	Johnson et al. (2017)
NFT	Sucrine	35-81	-	Delaide et al. (2016)
NFT	Verônica	86-96	2.27	Geisenhoff et al. (2016)
NFT	Green Oak Leaf	-	4.13	Lennard and Leonard (2006)
NFT	Pira verde	104-200	2-4	Jordan et al. (2018)

[1] Average of three cultivars: Jericho, Outredgeous and Flash Trout Back