Improving water management in European catfish recirculating aquaculture systems through catfish-lettuce aquaponics

(Article begins on next page)

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2 **lettuce aquaponics**

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14 **Abstract**

15 In the context of climate change and population growth, aquaculture plays an important role for food security,

16 employment and economic development. Intensive recirculating aquaculture systems (RAS) allow to treat

17 and recycle fish effluents to reduce waste concentration in outflow water thereby reducing environmental

18 contamination. RAS sustainability may be further improved using aquaponics, a circular productive system

19 in which RAS wastewater is recovered for crop cultivation and recycled back to the fish tanks. In this study,

20 water metabolism of a catfish RAS was assessed and the opportunity to produce lettuce with the RAS

21 effluent was tested. Crop growth and water consumption in aquaponics were compared to those experienced

22 in hydroponics at three nutrient solution concentration (EC of 1.6, 2.0 and 3.0 dS·m^{-1}), also considering water-

23 (WUE) and nitrogen- use efficiency (NUE). A scenario for converting the RAS in a catfish-lettuce aquaponic

24 system was, then, proposed.

25 The RAS water balance included an input of 555 L·day^{-1}, out of which 32 L·day^{-1} were lost by evaporation

26 from the tubs whereas 460 L·day^{-1} were discarded. The lettuce yield, NUE and WUE in aquaponics were

27 respectively 20.3%, 22.3% and 20.6% lower than those obtained in hydroponics. Best performances in

28 hydroponics were achieved with EC of 2.0 dS m^{-1}. No difference in term of water consumption arose between

29 the treatments, with average water use of 46 mL·plant^{-1}·day^{-1}.

30 Considering the current RAS productivity of 329 kg year^{-1}, a 10 m^2 raft system hosting 160 lettuces would

31 satisfy the nitrogen filtration demand. Once closed the water loop between the two productive sub-units, the

32 current water input of 532 L·day^{-1} could be reduced to the amount needed to replace the water lost by

33 evaporation (50 L·day^{-1}) and the RAS water output would decrease from 555 to 103 L·day^{-1}.
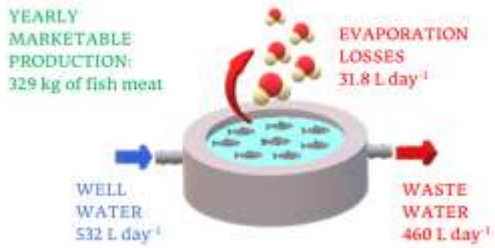
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35 **Keywords: Aquaponics, RAS, electrical conductivity, water use efficiency, sustainability**
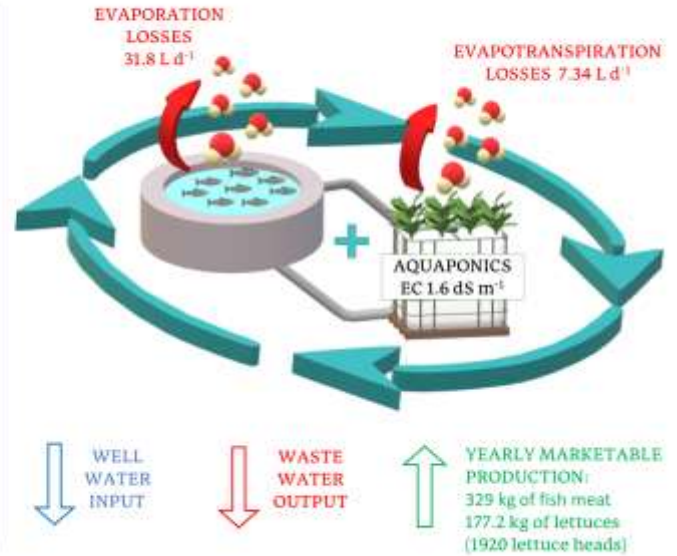
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Graphical Abstract

1. Introduction

World population is expected to increase between 20% and 30% by 2050, growing from 7.7 billion people to between 9.2 and 10.2 billion. Accordingly, global food demand is foreseen to increase by 60% by 2025 (Alexandros and Bruinsma, 2012). Concurrently, the global water consumption, already risen by 600% in the last century, will keep growing at a 1% yearly rate Wada et al., (2016) In this framework, the FAO Fisheries and Aquaculture Department (FAO, 2018) highlighted the important role of fisheries and aquaculture in boosting food and nutrition security, job employment and income generation for local communities. Today aquaculture (e.i. the cultivation of aquatic organisms in natural or controlled marine or freshwater environments) accounts for over 50% of the fish destined for human consumption, providing a primary source of protein and essential micronutrients worldwide (FAO, 2018). Current aquaculture systems range from extensive to intensive, depending on the level of inputs, the fish stocking density, and the degree of management. The adoption of intensive land-based systems located close to the markets, i.e. in the areas with high population density, is rapidly growing. Intensive fish farming systems can be categorized in "flow-

through" and "RAS" (Recirculating Aquaculture System). The former are open-systems in which the clean water flows once and is discharged thereafter. They are common in regions with high water availability, but their use is becoming always more limited due to the stringent water regulations regarding wastewater discharges into natural water bodies. The effluents from these open systems, containing residuals of uneaten food and high concentrations of nitrogen and phosphorus, can in fact cause oxygen depletion and eutrophication in the receiving water bodies (Martins et al., 2010). In the RAS, instead, only less than 10% of the total water volume needs to be daily discarded (Timmons and Ebeling, 2017). These systems are provided of mechanical and biological filters and additional water treatment components to depurate water from pollutants and allowing diseases control. Through this filtration process, the same volume of water can be continuously recirculated within the system while only a limited amount needs to be replaced with fresh water to avoid excessive nutrient loading.

Despite the introduction of RAS in aquaculture already contributed to downsizing the wastewater emissions into the environment, the disposing of this water is still a constant concern for aquaculture operators, especially now that environmental measures are evolving toward the concept of zero emission circular economy (EU, 2018). In this context, the set-up of closed-loop productive systems with low- or no-emissions, such as the aquaponics (e.g. a soilless system for crop production integrating aquaculture and hydroponics) concept, is raising growing interest (Endut et al., 2016). A key advantage of aquaponics is the symbiotic relationship between the plants and the fishes of the horticultural and aquaculture systems, respectively, which can be connected through the recirculation of the water flow. The fish dejections in the outflow water from the aquaculture system provide nutrients for the plants growth in the horticultural one, whereas plants, in turn, clean and filter the water that can be reused back to the fish tank (Goddek et al., 2015). This mutual exchange depends on the action of two different groups of bacteria, namely *Nitrosomonas spp.* and *Nitrobacter spp*. These bacteria oxidize the ammonia and nitrites excreted by the fishes to nitrates, which are easier to absorb by the plant roots (Rakocy et al., 2006). When an appropriate balance between the fish waste generation and the plants' nutrient uptake is achieved, the daily water consumption can be reduced to the water required for replacing the losses by evapotranspiration (Timmons and Ebeling, 2017). Accordingly, the discharge of effluents into the environment is reduced. In this sense, aquaponics promotes the minimization of by-product flows from economic activities by employing them as

4

81   resources in another activity, thereby contributing to the fulfilment of the goals of circular economy (EU,

82   2018).

83   Previous researches positively evaluated the waste-to-input aquaponic technology as a sustainable approach to

84   manage RAS wastewater, assessing the plants potential in utilizing nutrients from fishery effluents and their

85   contribution in maintaining a proper level of water quality (Endut et al., 2016; Espinosa Moya et al., 2017).

86   The goal of the present research is, then, to measure the water consumption of a pre-existing catfish RAS and

87   to make a preliminary evaluation of the potential use of its wastewater for lettuce production in hydroponics,

88   pursuant to the aquaponic principles. The specific objectives are to (a) quantify the water metabolism and

89   losses of the existing aquaculture system, (b) compare the lettuce growth (i.e. yield, Water Use Efficiency -

90   WUE - and Nitrogen Use Efficiency - NUE) in aquaponics vs conventional hydroponics, and (c) propose a

91   design scenario to convert the aquaculture system into a catfish-lettuce aquaponic system. A set of experiments

92   were therefore implemented in Soest (Germany) to address these research questions.

93

94   **2. Materials and methods**

95   **2.1. Case study**

96   Data collection was conducted at the experimental Recirculating Aquaculture System (RAS) of the South

97   Westphalia University of Applied Sciences (SWUAS) in Soest (Germany) between June 2016 and July 2017.

98   This plant was created in 2015 and consisted of three fish tanks of 1100 L each, filled up independently with

99   a water inflow processed in a sedimenter (460 L), a biofilter (nitrification process), and a water heater (800

100   L). The water outflow from the fish tanks was channeled to the sedimenter for solid removal and, then, re-

101   directed to the biofilter, thereby closing the water cycle. A certain amount of waste-water, however, was

102   discarded by the system and replaced by fresh water in order to dilute contaminant concentration and keeping

103   safe life condition both for fishes and bacteria.

104   Three different sizes of European Catfish (*Silurus glanis*) fingerlings (50, 300 and 400 g), with a stocking

105   density of 90-100 $kg \cdot m^{-3}$, were separately farmed in each fish tank. Feeding rates were set as a percentage of

106   the total fish biomass, starting from 4% for juveniles to 1.5% for adults. The fish feed used was commercial

107   diet pellet of 2 mm diameter for small-size fishes and 4.5 mm for large-size fishes (Aller Aqua Group,

108   Christiansfeld, Denmark) with 54% protein and 20% fat.

5

109

2.2. Experimental setup

The experiment was carried out in two phases. First, an experimental protocol was developed to quantify the

water metabolism and the water losses of the aquaculture system. Subsequently, a small scale Deep Water

Culture (DWC) hydroponic system was set up in order to evaluate lettuce (*Lactuca sativa* L. cv. Salanova

multileaf) yield and water consumption either using the RAS effluent or three hydroponic solutions with

different nutrient concentrations.

116

2.2.1. RAS water balance and efficiency parameters

The daily water balance of the RAS unit was calculated (Eq. 1) including all water inputs and outputs of the

water metabolism occurring in the RAS room (Fig. 1). The considered water inputs were the consumption of

fresh well water (Q_{ww}) and the water vapour that entered the room through ventilation (Q_{v_in}). The water outputs

were the evaporation taking place from the biofilter (Q_b), the sedimenter (Q_s), the fish tanks (Q_{ft}) and the sump

tank (Q_{st}), the water assimilated by fishes (Q_f), the water vapour that escaped the room through ventilation

(Q_{v_out}), and the water discarded (Q_w).

124

$$Water\ inputs = Water\ outputs$$

$$Tap\ water\ consumption\ (Q_{ww}) + Ventilation\ (Q_{v\_in}) = Evaporation\ (Q_b+Q_s+Q_{ft}+Q_{st}) + Fish\ water$$

$$assimilation\ (Q_f) + Ventilation\ (Q_{v\_out}) + Wastewater\ (Q_w) \qquad \text{[Eq. 1]}$$

128

Methods for defining each element of Eq. 1 are described below.

130

Water consumption. The amount of well water entering the system was measured daily with a water meter.

132

Ventilation. The water inputs and outputs as water vapour through the ventilation system of the room

(expressed as kg H_2O s^{-1}) were calculated according to Eq. 2, based on the absolute humidity (AH, g·m^{-3}), the

air flow speed (v, m·s^{-1}), and the area of the section crossed by the airflow (A_w, m^2).

136

$$137 \qquad Q_w \left[\frac{\text{kg H}_2\text{O}}{\text{s}}\right] = AH \left[\frac{\text{kg}}{\text{m}^3}\right] \cdot v \left[\frac{\text{m}}{\text{s}}\right] \cdot A_w [\text{m}^2] \qquad \text{[Eq. 2]}$$

The absolute humidity was calculated by employing an on-line psychrometric chart (https://www.rotronic.com) based on air pressure, air temperature, and relative humidity of the airflow. These parameters were measured 8 times in one month and the average values were used in the on-line tool. The air flow speed was measured with a propeller anemometer.

Evaporation. The water evaporation produced in the sedimenter, the fish tanks and the sump tank was calculated applying the Eq. 3, based on the evaporation coefficient (θ, $\text{kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$), the water surface area (A_s, m^2), and the difference between the saturated air maximum humidity ratio (x_s, kg $\text{H}_2\text{O} \cdot \text{kg}^{-1}$ of dry air) and the actual air humidity ratio (x, kg $\text{H}_2\text{O} \cdot \text{kg}^{-1}$ of dry air) above the water surface.

$$Q_i \left[\frac{\text{kg H}_2\text{O}}{\text{d}}\right] = 24 \cdot \theta \left[\frac{\text{kg}}{\text{m}^2 \cdot \text{h}}\right] \cdot A_s [\text{m}^2] \cdot (x_s - x) \left[\frac{\text{kg H}_2\text{O}}{\text{kg dry air}}\right] \qquad \text{[Eq. 3]}$$

The evaporation coefficient, θ, results from Eq. 4, where *v* is the velocity of the air above the water surface ($\text{m} \cdot \text{s}^{-1}$).

$$\theta \left[\frac{\text{kg}}{\text{m}^2 \cdot \text{h}}\right] = 25 + 19 v \left[\frac{\text{m}}{\text{s}}\right] \qquad \text{[Eq. 4]}$$

Note that the units of θ do not match with each other as it is a purely empirical formula.

The actual air humidity ratio (x) can be expressed as the ratio between the partial pressure of vapor in moist air (pw) to the atmospheric pressure of moist air (pa), where the factor 0.622 is the ratio between the molecular weight of water vapour (18.015 $\text{g} \cdot \text{mol}^{-1}$) and the average molecular weight of the other atmospheric gases (28.965 g mol^{-1}) (Shi et al., 2017) (Eq. 5).

$$x = \frac{0.662 \text{ pw [Pa]}}{\text{pa [Pa]} - \text{pw [Pa]}} \qquad \text{[Eq. 5]}$$

7

The actual air humidity ratio and the saturated air humidity ratio were calculated based on the air relative humidity, the air temperature, and the atmospheric pressure, using two online calculators of the thermodynamic properties of moist air (https://www.rotronic.com and http://www.tlv.com), according to Hyland and Wexler (1983). The relative humidity and the temperature of the air above the water surfaces of the fish tanks, the sedimenter and the sump were measured with three different sensors, recording data each ten seconds. The air speed at the water surface level was assumed as $0.05 \ \text{m} \cdot \text{s}^{-1}$ (Smith et al., 2014).

The water evaporation from the biofilter was calculated considering the difference between the biofilter ventilation outflow humidity when the biofilter is switched on and when it is off (Eq. 6).

$$Q_b \left[\frac{\text{kg H}_2\text{O}}{\text{s}} \right] = Q_{b,on} \left[\frac{\text{kg H}_2\text{O}}{\text{s}} \right] - Q_{b,off} \left[\frac{\text{kg H}_2\text{O}}{\text{s}} \right] =$$

$$\left(AH \left[\frac{\text{kg}}{\text{m}^3} \right] \cdot v \left[\frac{\text{m}}{\text{s}} \right] \cdot A_w [\text{m}^2] \right)_{on} - \left(AH \left[\frac{\text{kg}}{\text{m}^3} \right] \cdot v \left[\frac{\text{m}}{\text{s}} \right] \cdot A_w [\text{m}^2] \right)_{off} \qquad \text{[Eq. 6]}$$

Fish water assimilation. The fish water assimilation (L day^{-1}) was calculated by assuming water being 78.11% of the final fresh body weight of European catfish (Żmijewski et al., 2006). The final amount of water stored in the fish biomass was divided by the days of the growing cycle (365).

Wastewater. The amount of discarded water equals the capacity of the sedimenter, which is emptied daily.
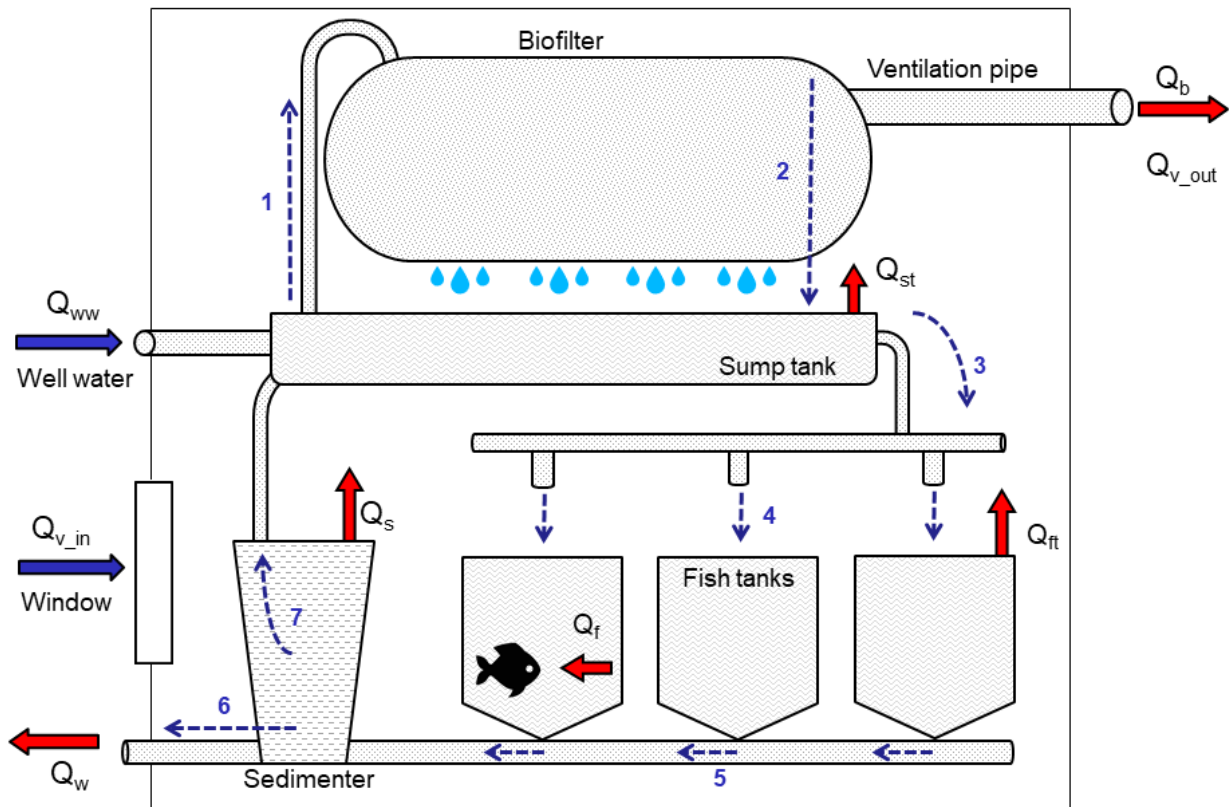
Figure 1. Graphical representation of the water flows across the aquaculture system. Dashed lines indicate the water flow: the well water enters in the sump tank and is raised to the top of the biofilter (1), falls through the biofilter net (2) and drops down again in the sump tank; from here it is distributed in the three fish tanks (3 -4); then, flows towards the sedimenter (5) and, once filtered, cycle back to the sump tank (7), from where restarts its cycle. Once a day, then, the sedimenter is emptied (6). The blue arrows represent the water input (Q_{ww} Well water consumption, Q_{v_in} Vapour flow entering through the ventilation system). The red arrows represent the water output (Q_{v_out} Vapour flow exiting through the ventilation system, Q_f Water assimilated by fishes, Q_{ft} Water evaporated by the fish tanks, Q_s Water evaporated by the sedimenter, Q_{st} Water evaporated by the sump tank, Q_b Water evaporated from the biofilter, Q_w Water discarded by the system).

The RAS efficiency was, finally, evaluated in term of water use (m^3 H_2O kg^{-1} FW), by dividing the total annual water inflow of the system (m^3) by the average annual fish fresh yield (kg) (Verdegem et al., 2006).

2.2.2 Evaluation of lettuce cultivation in aquaponics vs traditional hydroponics

9

Eight boxes of 30 L were employed to grow up the plants, covered by a polystyrene sheet with ten holes to support the seedlings (transplanted at sixth leaf stage). Four water treatments were imposed at different electrical conductivity (EC): Aqua (water from the RAS with EC 1.6 dS m^{-1}), Hydro 1.6 (hydroponic solution with EC 1.6 dS m^{-1}), Hydro 2.0 (hydroponic solution with EC 2.0 dS m^{-1}) and Hydro 3.0 (hydroponic solution with EC 3.0 dS m^{-1}). The initial composition, pH, EC and C:N ratio of the four nutrient solutions are described in Table 1. All the boxes were connected to an air pump to guarantee oxygenation to the nutrient solution. Air humidity and temperature were recorded by a sensor every ten minutes.

Table 1: Composition of the nutrient solutions of the treatments Aqua, Hydro 1.6, 2.0 and 3.0, respectively.

		Aqua	Hydro 1.6	Hydro 2.0	Hydro 3.0
pH		7.3	6.9	6.7	6.5
EC	dS·m^{-1}	1.6	1.6	2	3
NH$_4^+$	mmol L^{-1}	0.09	0.27	0.33	0.5
NO$_3^-$	mmol L^{-1}	7.36	6.94	8.73	13.24
K$^+$	mmol L^{-1}	0.58	6.13	7.67	11.5
Na$^+$	mmol L^{-1}	4.32	0.9	1.1	1.2
Ca^{2+}	mmol L^{-1}	3.4	2.93	3.67	5.5
Mg^{2+}	mmol L^{-1}	0.43	0.8	1	1.5
Cl$^-$	mmol L^{-1}	2.77	1.07	1.33	2
S	mmol L^{-1}	1.35	1.07	1.33	2
HCO$_3^-$	mmol L^{-1}	0.72	0.08	0.1	0.15
P	mmol L^{-1}	0.09	1.07	1.33	2
Fe	μmol L^{-1}	0.28	21.33	26.67	40
Mn	μmol L^{-1}	0.2	2.67	3.33	5
Zn	μmol L^{-1}	2.22	2.67	3.33	5

B	μmol L^{-1}	29.83	26.67	33.33	50
Cu	μmol L^{-1}	0.53	0.53	0.67	1
Mo	μmol L^{-1}	<0.1	0.27	0.33	0.5
N tot	mg L^{-1}	105.05	100.93	126.94	192.44
C:N ratio		0.083	0.010	0.009	0.009

Water consumptions. The evapotranspirative losses (ET$_p$) were measured by reading the water level decrease inside the boxes through a graduated scale.

Biomass production. Once harvested, plants' shoots were immediately separated from roots and weighted in order to obtain the fresh weight (FW). Dry weight (DW) was determined after oven-drying the sample for three days at 105°C. According to Qiansheng et al. (2018) the lettuce root biomass in hydroponics accounts for only about the 10% of the total fresh biomass, therefore it was considered negligible and not taken into account for the calculation of the below-listed parameters. The dry matter percentage (DM) was calculated by the ratio between the lettuce head dry (g) and fresh (g) weight, and expressed as percentage.

C:N ratio: Total leaf N and C content, were measured on dry samples with a LECO CNS2000 elemental analyzer (LECO Corporation, St. Joseph, MI, USA).

WUE. Total water use efficiency (g FW L^{-1} H$_2$O) was calculated as the ratio of the FW (g) of the plants of each box to the relative total water consumption (L) (Fallovo et al., 2009).

NUE. Water samples of the nutrient solution were collected at the beginning of exp. 2 and 3. These were analyzed for main macro and microelements by the Eurofins Agro water test laboratories (Binnenhaven 5 NL - 6709 PD, Wageningen, The Netherlands). The NUE (g FW mg^{-1} N) was calculated by the ratio between the average fresh weight of the plants of each box (g) and the total elemental nitrogen available at the beginning of the growing cycle in the nutrient solution (mg) (Benincasa et al., 2011).

230 *2.2.3. Design for a closed water cycle*

231 With the aim of boosting the resources efficiency of the aquaculture system, a DWC hydroponic unit can be

232 introduced in the already existing RAS to recover its water discharge and recycle it as nutrient solution for

233 lettuce cultivation. In such a system, water requirements are only limited to those needed to compensate

234 evaporative water losses. Plants in aquaponics play a key role in water quality control notably as concerns N-

235 and P-containing nutrients (Goddek et al., 2015). For a proper operation of an aquaponics system, therefore,

236 the plant cultivation must be dimensioned to the fish stocking density in order to ensure an efficient control of

237 nutrient load.

238 Keeping the size of the actual RAS system, a design for an aquaponic system for lettuce-catfish production is

239 here proposed. The proportion of the DWC beds is calculated through a parameter elaborated by Rakocy et al.

240 (2006) called Feeding Rate Ratio (FRR) (Eq. 7), which express the relation between the fish feed amount

241 introduced in the system and the plant growing area.

242

243
$$\text{FRR} \left[\frac{g}{m^2 d}\right] = \frac{\text{fish feed [g]}}{\text{plant area } [m^2] \cdot \text{day}} \qquad \text{[Eq. 7]}$$

244

245 The optimum FRR for raft hydroponics varies from 60 to 100 $g \cdot m^{-2} \cdot day^{-1}$ (Rakocy et al., 2006). Accordingly,

246 for the purpose of this study, a FRR of 80 $g \cdot m^2 \cdot day^{-1}$ for raft hydroponic lettuce production was set. The

247 computations were done assuming that the production should be split and harvested in staggered phases to

248 keep constant the optimal stocking density (Rakocy et al., 2006). A fish productive cycle of 12 months was

249 assumed to allow obtaining adults of 2 kg (with a final stocking density of 100 $kg \cdot m^{-3}$) from fingerlings of 300

250 g (data established according to the performance of previous cycles and literature data, e.g. Żmijewski et al.,

251 2006). The fish production should be staggered to harvest once a year from each tank, with a time step of about

252 17 weeks (the three harvests being distributed along the year). Starting from a plant at the sixth unfolded leaf

253 stage, a productive growing cycle of 4 weeks was considered, setting a plant density of 16 plants m^{-2} (Rakocy

254 et al., 2006).

255

256 **2.3. Statistical analysis**

The experimental data were treated statistically using CoStat software package. A two-way analysis of variance (ANOVA) at 95% confidence was performed to test the influence of the growing cycle and the water source on evapotranspiration losses, biomass production, WUE and NUE. Means were compared using the LSD test at $P \leq 0.05$.

3. Results and discussion

3.1. RAS water balance and efficiency parameters

The results of the water balance on the aquaculture unit showed that about 555 L of water flow through the system every day. A description of the water metabolism elements is reported in Table 2.

Table 2. Daily water input and output within the aquaculture system.

AQUACULTURE SYSTEMS			
INPUT		OUTPUT	
Air absolute humidity (kg·day^{-1})	22.9 ± 3.0	Air absolute humidity (kg·day^{-1})	52.6 ± 1.41
		Biofilter (kg·day^{-1})	17.7 ± 1.52
		Sump tank (kg·day^{-1})	6.7 ± 0.26
		Fish tanks (kg·day^{-1})	5.8 ± 0.16
Well water (L·day^{-1})	532	Sedimenter (kg·day^{-1})	0.9 ± 0.09
		Fish water assimilation (L·day^{-1})	0.70
		Water discharge (L·day^{-1})	460
		Undetermined losses (L·day^{-1})	10.45
TOTAL INPUT	554.9 ± 3.0	TOTAL OUTPUT	554.9 ± 3.44

The biofilter produced the highest evaporation losses (17.7 L·day^{-1}), which resulted 62.5%, 67.2% and 95.2% higher than those generated from the sump, the fish tanks and the sedimenter (6.7, 5.8, and, 0.9 L·day^{-1}), respectively. This could be due to a peculiarity of the biofilter used in this system which exploits the water evaporation to cool down the air temperature.

Water use for catfish in the experimental RAS was 0.59 m^3·kg^{-1}, 2.5 folds higher than that recorded for tilapia production in RAS (0.24 m^3·kg^{-1}) (Eurofish, 2009). Previous experiences also suggest that water consumption values are highly variable in response to the fish productive system adopted: they range from 0.5 to 0.7 m^3 kg$^-$

276   [1] in a super-intensive recirculating system (Verdegem et al., 2006) or average 1 $m^3 \cdot kg^{-1}$ in a RAS system

277   (Bregnballe, 2015) but also increase up to 45 $m^3 \cdot kg^{-1}$ in an extensive pond system (Verdegem et al., 2006).

278   The average fish yield of the studied RAS was 329 $kg \cdot year^{-1}$, which corresponds to a total amount of water

279   assimilated by the fish of 257 L.

280

281   **3.2 Evaluation of lettuce cultivation in aquaponics vs traditional hydroponics**

282

283   *Climatic condition*. Exp. 1 was performed between July and August 2016. The minimum, average and

284   maximum temperatures were respectively 17.0, 28.4 and 46.0°C in July and 13.7, 23.5 and 34.4°C in August.

285   The mean daily temperature was higher than the average monthly temperature for 13 days. Exp. 2 was

286   performed between the last days of September and October 2016. The minimum, average and maximum

287   temperatures were respectively 14.5, 21.1 and 34.0°C in September and 12.0, 18.0 and 30.5°C in October. The

288   mean daily temperature was higher than the average temperature for 17 days. Exp. 3 was performed between

289   June and July 2017. The minimum, average and maximum temperatures were respectively 16.0, 24.3 and

290   50.0°C in June and 17.0, 23.9 and 39.0°C in July. Mean daily temperature was higher than the average

291   temperature for 20 days. The absence of an automated system for temperature management did not allow to

292   prevent the occurrence of extreme temperatures.

293

294   *Water and nutrient consumption*. The water consumptions did not show statistically significant differences

295   (P-value>0.05) among the four treatments (Hydro 1.6, Hydro 2.0, Hydro 3.0 and Aqua), although seasonal

296   variations in total water consumption were observed among the three experiments. The average daily amount

297   of evapotranspiration was 52.0, 27.3 and 58.4 $mL \cdot head^{-1} \cdot day^{-1}$ for the exp. 1, 2 and 3, respectively. Similar

298   results were observed by Ciolkosz et al. (1998) and Conversa et al. (2004), who recorded respectively ET

299   values comprised between 24 and 178 $mL \cdot head^{-1} \cdot day^{-1}$ and between 76 to 214 $mL \cdot head^{-1} \cdot day^{-1}$ in lettuce grown

300   in hydroponics. The lowest ET value were recorded in the exp. 2, which coincided with the lower temperatures

301   experienced during the autumn season. The composition of the nutrient solutions at the end of the experiments

302   is reported in Table 3. In all cycles the EC of the treatments Hydro 1.6 and 2.0 was reduced from the initial

303   value, whereas an increase in EC in both Aqua and Hydro 3.0 treatments was observed during cycles 1 and 3.

14

A pH increase was observed for all the nutrient solutions in every cycle, with special emphasis for the

treatments Hydro 1.6 and 2.0. The ammonium concentration dropped close to zero in all the treatments, while

the nitrate concentration increased, especially in hydroponic. The potassium, phosphorus, molybdenum and

manganese concentrations in aquaponics, already low at the beginning of the experiment, reached almost zero

at the end of the three cycles, while the final potassium and molybdenum concentration in hydroponics was

increased from the initial value, possibly as a consequence of water evaporation and root selective uptake

(Albornoz and Lieth, 2015). The aquaponics iron concentration, instead, remained almost constant or

increased, probably due to both the solution evaporation and the lower iron availability when pH is above 7.

Calcium concentration, as well, did not vary largely in aquaponics while it was one forth on average in the

other solutions. This might be attributed to the uptake competition played by the sodium ion, since its initial

concentration in aquaponics was 4-folds higher than in hydroponics (Albornoz and Lieth, 2015).

Table 3: Composition of the nutrient solutions of the treatments Aqua, Hydro 1.6, 2.0 and 3.0 at the end of the

three experiments.

		Aqua			Hydro 1.6			Hydro 2.0			Hydro 3.0		
Cycle		1	2	3	1	2	3	1	2	3	1	2	3
pH		7,52	7,76	7,65	7,55	7,9	7,7	6,9	7,14	7,7	6,4	7,05	6,95
EC	$dS·m^{-1}$	1,85	1,3	1,8	1,5	1,2	1,25	1,8	1,45	1,25	3,25	2,65	3,05
NH_4^+	$mmol\ L^{-1}$	<0,1	<0,1	< 0,1	<0,1	<0,1	< 0,1	<0,1	<0,1	< 0,1	<0,1	<0,1	< 0,1
NO_3^-	$mmol\ L^{-1}$	9,2	5,7	4,85	1,8	0,4	< 0,1	3,45	1,6	< 0,1	8,7	6,3	4,25
K^+	$mmol\ L^{-1}$	0	<0,1	< 0,2	9	6,45	8,4	11,9	8,35	8,4	24,1	17,6	22,6
Na^+	$mmol\ L^{-1}$	5,35	3,55	9,65	1,4	1,4	1,95	1,2	1,3	1,95	1,35	1,55	2,2
Ca^{2+}	$mmol\ L^{-1}$	4,8	3,5	4,5	0,65	0,65	0,75	0,85	0,85	0,75	2	1,4	1,1
Mg^{2+}	$mmol\ L^{-1}$	0,55	0,4	0,5	0,25	0,2	0,2	0,2	0,2	0,2	0,3	0,3	0,2
Cl^-	$mmol\ L^{-1}$	3,85	2,55	5,05	2,75	2,55	2,25	3,05	2,8	2,25	5,1	4,75	5,65
S	$mmol\ L^{-1}$	2,05	1,5	2,55	2,9	2,35	3,8	3,25	2,75	3,8	5,35	4,35	6,35
HCO_3^-	$mmol\ L^{-1}$	0,15	0,8	3,85	0,4	1,5	0,95	0,1	0,9	0,95	<0,1	0,35	0,2
P	$mmol\ L^{-1}$	<0,04	<0,04	< 0,04	0,575	0,42	0,81	1,35	0,59	0,81	3,055	1,325	2,32
Fe	$µmol\ L^{-1}$	0,35	0,2	0,55	21,5	12	28,5	11,15	16,5	28,5	17,5	23	81,5
Mn	$µmol\ L^{-1}$	0,1	< 0,1	< 0,1	0,2	0,15	0,15	0,1	0,15	0,15	1,75	0,8	0,25
Zn	$µmol\ L^{-1}$	2,4	2,85	0,15	24	7,4	8,35	48,5	8,65	8,35	75	30,5	14

|													
B	μmol L^{-1}	36	21,5	91	53	44	82	65,5	58	82	110	99,5	143
Cu	μmol L^{-1}	0,35	0,45	0,95	1,3	1,4	3,15	1,1	1,7	3,15	2,05	1,7	3,85
Mo	μmol L^{-1}	0	< 0,1	< 0,1	1,7	0,4	0,85	1,35	0,4	0,85	1,55	0,6	1,3
N tot	mg L^{-1}	130,12	81,09	69,19	26,47	6,86	2,52	49,58	23,67	2,52	123,12	89,50	60,79
C:N ratio		0,014	0,118	0,668	0,181	2,625	4,526	0,024	0,457	4,526	0,009	0,047	0,040

318

319 *Yield.* Considering that not statistically significant interactions were detected between the two experimental

320 factors (growing cycle and water source), mean values are used for presenting yield data. Lettuce grew the

321 least in aquaponics (92.3 g·plant^{-1}), whereas higher biomass productions were achieved in the Hydro 2.0 and

322 3.0 (mean value of 120.3 g·plant^{-1}) similarly to previous studies on aeroponically grown lettuce (Albornoz and

323 Lieth, 2015). The absence of yield differences between Hydro 2.0 and Hydro 3.0 shows that nutrients in the

324 latter resulted in luxury consumption rather than increasing biomass production nor leading to salinity

325 symptoms (Nozzi et al., 2018).

326 A lower performance in aquaponics versus hydroponics was previously described by El Sayed and Samir

327 (2015), and Johnson et al. (2017), whereas Pantanella et al. (2012) and Delaide et al. (2016) did not observe

328 differences in yield among the two growing systems. The lower yield in aquaponics may be associated to

329 reduced K$^+$, P$^+$, Fe^{2+} and Mn^{2+} concentrations in the nutrient solution (Rakocy et al., 2007). The amount of

330 these nutrients in aquaponics is often not adequate to the plant requirements due to their low concentration in

331 most of the commercial fish feeding formulations, and because part of them precipitate and is lost in the form

332 of fish solid excretion (Rakocy et al., 2007; Goddek et al., 2015). Besides, to counteract the pH drops due to

333 the bacterial nitrification process, a bicarbonate buffer was periodically added to the RAS circulating medium.

334 The subsequent higher HCO$_3^-$ concentration in the aquaponics solution, combined with the higher pH (Table

335 1), may have contributed to reduce the nutrient solubility and absorbability (Pignata et al., 2017), especially

336 for phosphorous, iron, manganese, magnesium and calcium (Trejo-Téllez and Gómez-Merino, 2012).

337 Furthermore, it has also been suggested that the bacterial community from the aquaponics may compromise

338 the nutrient availability by consuming nutrients or by increasing the energetic cost to import them across the

339 root interface (Wielgosz et al., 2017). Goddek et al. (2015) stated that aquaponics can match hydroponics when

340 all the parameters are controlled, and the bacterial community is fully mature. In the current study, the nutrient

16

imbalance in the aquaponics water solution may indicate that the fish stocking rate and/or their dietary composition need to be adjusted to supply the plants with the proper nutrients amount.

Despite the lowest yield, however, the DM% and C:N ratio in leaf tissues were significantly higher in aquaponics than in hydroponics (Fig. 1). This may depend on the different nutrient composition and availability in the two growing systems. As already mentioned, indeed, the C:N ratio of the nutrient solution in aquaponics was, 8.7-fold higher than the average value in the three hydroponic treatments (Table 1). Moreover, as stated by Nozzi et al. (2018) a P deficiency in the nutrient solution (Table 1) reduces the root N uptake. This, in turn, induces accumulation of non-structural carbohydrates (e.g. organic acids and sugars) for the cellular osmoregulation, resulting in a DM increase and, consequently, also in changes in the C:N ratio. The absence of significant variations in DM among the hydroponic treatments, on the other hand, is in line with the result of Ünlükara et al. (2008) and Scuderi et al. (2009) which reported a nearly constant DM content in plants growing under variable salinities, even over 3 dSm^{-1}.
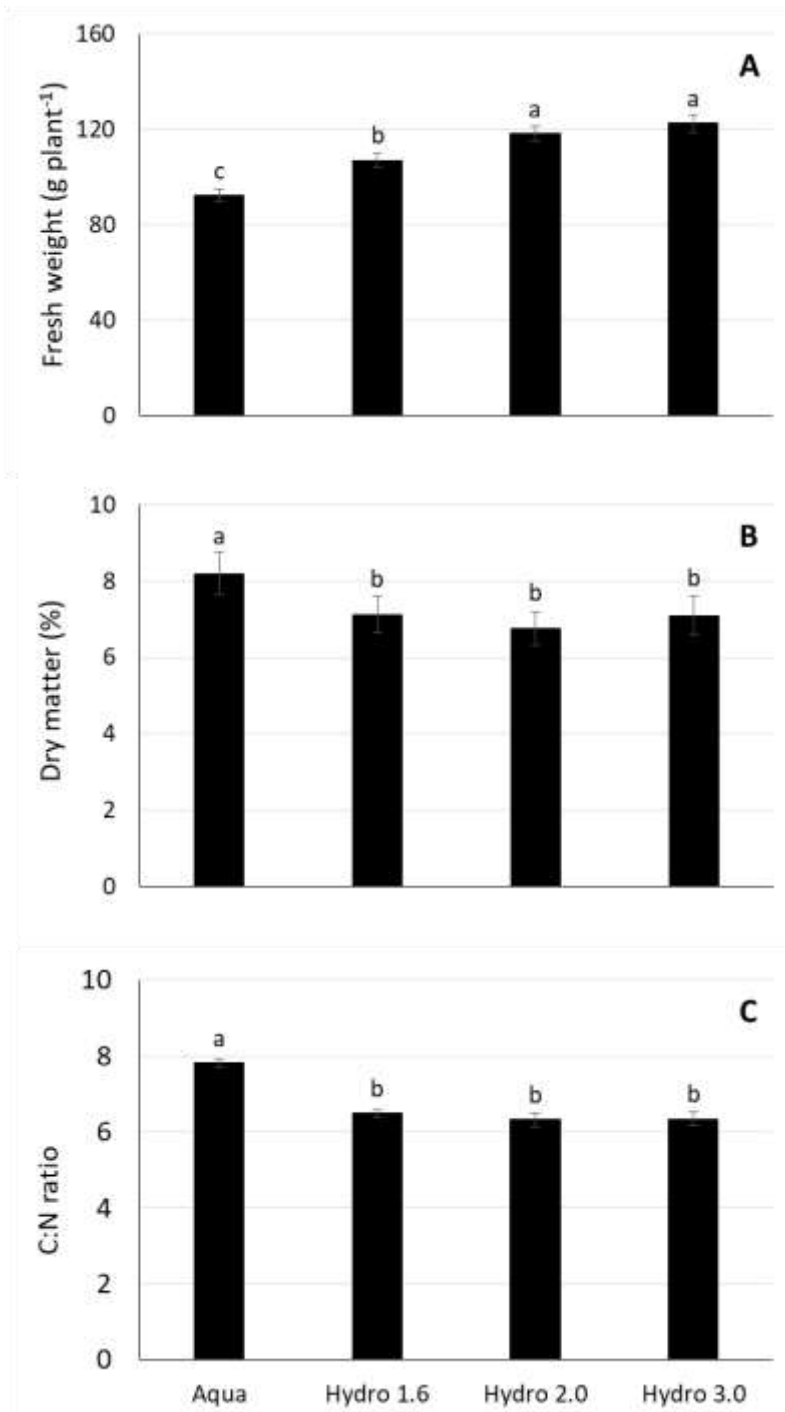
Figure 1. Fresh weight (A), dry matter (B), and C:N ratio (C) of lettuce plants grown under different water regimes. Data referring to exp. 1, 2 and 3 are indicated as mean ± SE. Different letters indicate significant differences at P≤0.05.

NUE. Given that the interaction between the two experimental factors (growing cycle and water source) was not statistically significant, the mean values for NUE were used. In the hereby presented experiments, NUE in aquaponics (0.34 g FW·mg^{-1} N) was significantly lower than in Hydro 1.6 and 2.0 (0.5 g FW·mg^{-1} N on

18

average), but statistically non different from the Hydro 3.0 treatment (0.33 g FW·mg^{-1} N). The lower

performance in aquaponics may, again, depend on the different ratio of nitrogen forms in the nutrient solution.

Ammonia (NH$_4$-N) level in aquaponics was, in fact, below 0.1 mmol·L^{-1} (Table 1) due to the nitrification

operated by the bacteria of the RAS biofilter. Despite most plants prefer NO$_3^-$ over NH$_4^+$ as nitrogen source,

the NO$_3^-$ acquisition and assimilation is more energy demanding than ammonium and, then, a 1:3 ratio of

NH$_4^+$:NO$_3^-$, compared with nitrate alone as the sole source of N, showed to be beneficial to plant growth and

yield in hydroponics (Savvas et al., 2006).

Increasing the nitrogen fertilization and uptake may not necessarily lead to improved crop yield and NUE

(M'hamdi et al., 2014). A similar behaviour was observed in the present experiment when, rising the EC up to

3 dS·m^{-1}, (N concentration of 243 mg·L^{-1}), the yield did not increase, leading to a decrease in NUE (Fig. 2).

This is consistent with the findings of Stefanelli, Winkler and Jones (2011) who reported increased lettuce

NUE at N concentration from 40 to 75 mg·L^{-1}, reaching a plateau at 150 mg·L^{-1} and with no subsequent

increases between 400 and 2400 mg·L^{-1} N. Similarly, according to Mahlangu et al. (2016), a N concentration

of 100-120 mg·L^{-1} is enough to improve growth, yield and quality parameters of hydroponic lettuce. In the

present case, the N concentration at 2.0 dS·m^{-1} (162.0 mg·L^{-1} N) enhanced NUE and maximized the

production, while the increased nitrogen input in Hydro 3.0 (243 mg·L^{-1} N) resulted in a NUE decline with no

further yield increase.
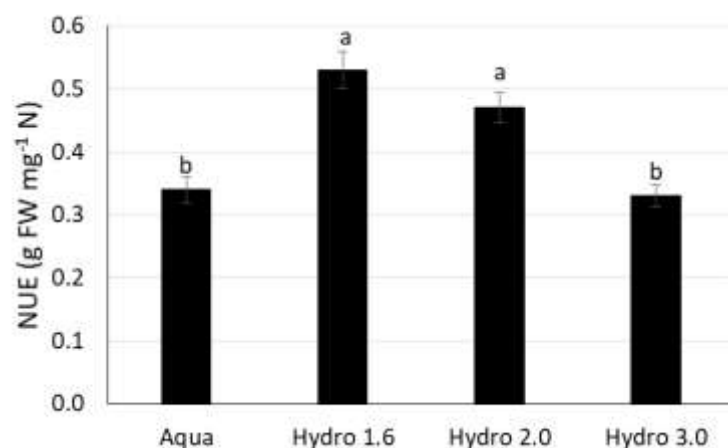
Figure 2. Nitrogen use efficiency (NUE) of lettuce plants grown under different water regimes. Data referring

to exp. 2 and 3 are indicated as mean ± SE. Different letters indicate significant differences at P≤0.05.

WUE. The interaction between the growing season and the water source significantly affected the lettuce WUE. Aquaponics always showed the lowest WUE [69.8 g FW·L^{-1} H$_2$O for exp. 1, 98.5 g FW·L^{-1} H$_2$O for exp. 2 and 48.1 g FW·L^{-1} H$_2$O for exp. 3] (Fig. 3). This is probably due to a decrease in the photosynthetic efficiency rather than in the leaf evaporation as no difference in water consumption arose among aquaponics and hydroponics treatm ents (De Costa and Ariyawansha, 1996). In addition, it is worth to mention that Na$^+$ concentration in aquaponics was 4-folds higher than in hydroponics (Table 1). As already observed by Tzortzakis (2009), moderate sodium stress is more likely to affect elemental absorption by competition than interfering with the root water uptake, leading to ions imbalance, restricted nutrient uptake and consequent yield reduction. The production of osmolytes to counteract the specific Na$^+$-related osmotic stress may be another justification of the higher leaf DM encountered in aquaponics. In conclusion, the nutrient imbalance in aquaponics, namely the higher sodium concentration combined with the lack in potassium, phosphorous, iron and manganese, had a more negative impact on plant yield and WUE then the higher water conductivity in the hydroponic treatments.

In hydroponics, different WUE trends were observed in the three cycles. In exp. 1 no WUE differences arose between the three treatments. In exp. 2, the WUE of the Hydro 2.0 and 3.0 treatments were comparable but resulted significantly higher than the Hydro 1.6. In exp. 3, significant differences could only be found between Hydro 1.6 and Hydro 3.0, the latter presenting higher values. According to the obtained results, it may be argued that an EC increase over 1.6 dS·m^{-1} could possibly boost WUE. Moreover, although significant differences could be observed between the treatments Hydro 1.6 and Hydro 3.0, the latter never differed significantly from the intermediate Hydro 2.0. Hence, bearing in mind the objective to contain the productive costs and the chemical input, using an EC of 2.0 in place of 1.6 dS·m^{-1} can boost the crop yield without interfering with the NUE and WUE. The lower WUE observed in the summer cycles (exp. 1 and 3) may be due to the higher solar radiation and temperature which may have increased the atmospheric evaporative demand and the plant respiratory losses (Fallovo et al., 2009) as compared with the autumn cycle (exp. 2). A similar behaviour was observed also by Shaban et al. (2016), who observed a WUE increase when lettuce was subjected to irrigation water cooling and shading. Lettuce, indeed, is a short-day cool season crop with an optimum temperature range of 7-24 °C (Shaban et al., 2016). Under warmer condition the plant increase the transpiration rate to regulate the leaf temperature, through the mechanism of

evaporative cooling. However, although transpiration is positively correlated to biomass accumulation, upon

elevate temperature the plant reduces its ability to regulate the water relations and further transpiration losses

do not provide extra biomass gain, lowering thereby the WUE (Zhang et al., 2015). The high temperature,

combined with the high radiation, may have also resulted in reaching the light saturation point, inducing

photoinhibition and stomatal closure (Hunt et al., 1984). Hence, it may be argued that the decreased

photosynthesis efficiency and carbon assimilation, associated with an increase in the canopy transpiration,

might have negatively affected the plant WUE during the two summer cycles.

The achieved WUE values are, however, consistent with the results of Chabite et al. (2017) that also

obtained values among 29.7 and 142.9 $g \cdot L^{-1}$ for lettuce grown using different nutrient solutions.
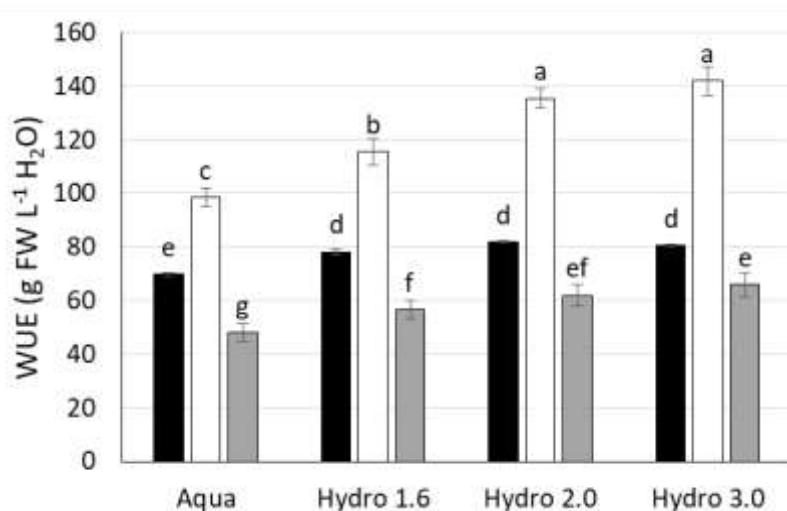
Figure 3. Water Use Efficiency (WUE) of lettuce plants grown under different water regimes. Black bars

represent results of exp. 1, white bar represent results of exp. 2, grey bar represent results of exp. 3. Data are

expressed as mean ± SE. Different letters indicate significant differences at P≤0.05.

3.2. Design proposal to convert the RAS into a catfish-lettuce aquaponic system

In this section, a design for introducing a lettuce DWC hydroponic unit into the already existing RAS is

proposed, with the goal to transform it in a closed productive aquaponic system.

According to Eq. 1 and the data from the Table 2, the total water input and output within the RAS consisted

of 554.9 $L \cdot day^{-1}$. The estimated potential catfish production of the current RAS is 329 $kg \cdot year^{-1}$. According to

432   the calculation procedure elaborated by Rakocy et al. (2006), a lettuce growth bed area of 9.63 m^2 is required

433   to satisfy the nitrogen filtration demand at this productive rate. Keeping the suggested plant density of 16 plants

434   m^{-2}, the projected 10 m^2 DWC plant may host up to 160 lettuces per month. According to the attained results

435   on the lettuce mean water consumption, i.e. 45.9 mL·head^{-1}·day^{-1}, an average water consumption (Q_{eva_p}) of

436   7.3 L·day^{-1} is expected for a raft system hosting 160 plants. The current well water input (Q_{ww} = 532 L·day^{-1})

437   could, therefore, be reduced to the amount needed to replace the water lost by evaporation from the RAS (Q_{eva_f}

438   = 41.6 L·day^{-1}), from the hydroponics tubs (Q_{eva_p} = 7.3 L·day^{-1}), and the summed water withheld in the fish

439   tissues (Q_f = 0.7 L·day^{-1}) (Figure 4). With the introduction of the proposed hydroponic unit, then, the RAS

440   water discharge (Q_w = 460 L·day^{-1}m^{-2}) will be fetched to supply the DWC system and the system water

441   metabolism will improve as the water output will decrease from 554.9 to 102.53 L·day^{-1} (Table 4).

442   By installing an environment control system in the greenhouse, the lettuce production can be realized

443   continuously over the 365-days cycle of catfish. A staggered crop production system, however, is suggested

444   to keep the water quality relatively constant and allow the lettuce harvest with regular cadency. Assuming a

445   30-day crop cycle, then, the lettuce production can be staggered so that four growth stages can be

446   simultaneously cultivated in one month and one-fourth of the lettuces can be weekly harvested (40 lettuce

447   heads). For the fish production, as well, three fish ages should be contemporary reared in the three tanks in

448   order to produce an effluent whose composition remains relatively constant. Accordingly, the fish from one

449   tank will be stocked once every four months, with an expected potential production of 82.3 kg quadrimester^{-1}.

450   The yearly production, then, will consist of 329 kg of fish meat plus 1920 lettuce heads, which correspond to

451   a biomass production of 17.7 kg·m^{-2}, if the average lettuce FW obtained in aquaponics during the hereby study

452   (92.3 g·plant^{-1}) is considered.

453
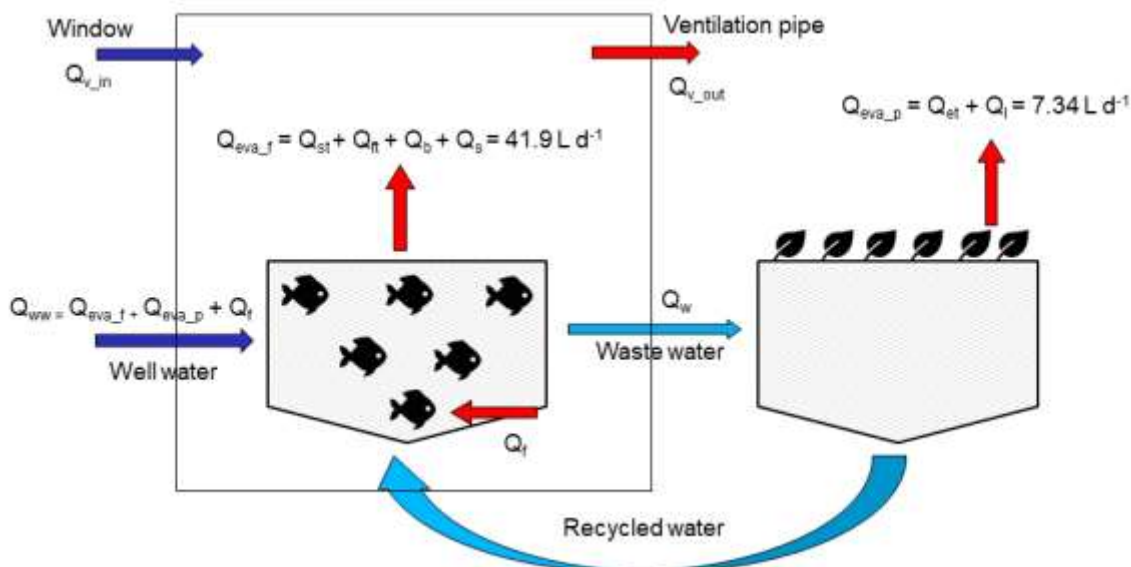
454

455 **Figure 4.** Graphical representation of the water flows across the proposed catfish-lettuce aquaponic system.

456 The dark-blu arrows represent the water input: Q_{ww} Well water consumption, Q_{v_in} Vapour flow entering

457 through the ventilation system. The red arrows represent the water output: Q_{eva_p} = (Q_{ft} Water evaporated

458 by the fish tanks + Q_s Water evaporated by the sedimenter + Q_{st} Water evaporated by the sump tank + Q_b

459 Water evaporated from the biofilter), Q_f Water assimilated by fishes, Q_{v_out} Vapour flow exiting through

460 the ventilation system, Q_w Water discarded by the system, Q_{eva_p} = (Q_{et} Water evaporated by the raft

461 hydroponic system + Q_l Water assimilated by the plant tissue. The light-blu arrows represent the circular

462 water pathway among the two aquaculture and hydroponic sub-units.

463

464 **Table 4**. Comparison of the water input-output and of the marketable products obtainable from the current

465 RAS system and from the proposed catfish-lettuce aquaponics system. All the water-related items are

466 expressed in L day^{-1}: Q_{ww} Well water consumption, Q_{v_in} Vapour flow entering through the ventilation

467 system, $Q_{eva\_}$ Water evaporated by the aquaculture tanks and/or the hydroponic tanks, Q_f Water assimilated

468 by fishes, Q_{v_out} Vapour flow exiting through the ventilation system, and Q_w Water discarded by the system.

Total water input (Q_{v_in} + Q_{ww})	Well water input (Q_{ww})	Total water output (Q_w + Q_{eva} + Q_f + Q_{v_out})	Water discarge (Q_w)	Evaporation losses (Q_{eva})	Yield

Current scenario	554.9	532	554.9	460	41.6	360 kg year^{-1} fish meat
Proposed scenario	72.84	49.64	102.53	/	48.94	360 kg year^{-1} fish meat 1920 lettuce heads year -1

469 **4. Conclusion**

470 The present study contributes to the research in aquaponics, offering innovative figures on the water

471 consumption of a catfish recirculating aquaculture and the potential for wastewater saving associated with

472 lettuce production in aquaponics. The results of this study indicated that the considered RAS aquaculture

473 system has a daily water consumption of 555 L·day^{-1}, out of which the 83% is direct water discharge from the

474 system while evaporation losses from the system' tubs account for 31 L·day^{-1} and humidity detraction from

475 the plant room accounts for 53 L·day^{-1}. With the introduction of a hydroponic component into the system, the

476 discharged water can be recovered and used as nutrient solution for a 10 m^2 raft hydroponic system. Additional

477 researches are, however, needed to lower the component of evaporative losses by the system.

478 The nutrients requiring supplementation in the hydroponic unit would be ammounium, potassium,

479 phosphorous, iron and manganese, whereas the amount of dissolved sodium and bicarbonate ions may be too

480 elevated to sustain plant productivity. Such nutrient imbalance may be the reason of the lower observed yield,

481 WUE and NUE in aquaponics. Given the already high level of nitrate and sodium, a further increase in the fish

482 stocking density should be avoided while the strategy of integrating the aquaponic solution with synthetic

483 mineral elements, as proposed by Delaide et al. (2016), could be tested to improve the nutrient solution

484 composition. This option would still allow reduced fertilizer costs and environmental impacts compared to

485 traditional hydroponic, but more in-depth investigations would be necessary to determine the nutrient

486 supplementation effects on fish physiology. A change in the fish feeding diets should also be considered. Fish

487 feed contains 0.1 to 0.3% added sodium (Mallick and Rahman, 2005), although such high concentrations is

488 not really necessary to fishes (Rakocy et al., 2007). In order to reduce the levels of Na$^+$ in the fishery

489 wastewater, then, alternative feed formulations having higher level of potassium and plant-protein, instead of

490 animal-protein, should be tested for combined catfish-lettuce growth. Finally, studies on the role played by

both microorganism and organic compounds on the crop performances could contribute to make this picture more complete.

In conclusion, the aquaponics system overall environmental sustainability builds on the avoided impact associated with both the RAS wastewater released into the environment and the less chemical input needed for lettuce hydroponic production as compared with two systems operating independently.

REFERENCES

Al-Hafedh, Y.S., Alam, A., Beltagi, M.S., 2008. Food Production and Water Conservation in a Recirculating Aquaponic System in Saudi Arabia at Different Ratios of Fish Feed to Plants. J. World Aquac. Soc. 39, 510–520. https://doi.org/https://doi.org/10.1111/j.1749-7345.2008.00181.x

Albornoz, F., Lieth, J.H., 2015. Over fertilization limits lettuce productivity because of osmotic stress. Chil. J. Agric. Res. 75, 284–290. https://doi.org/10.4067/S0718-58392015000400003

Alexandratos., N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision Global Perspective Studies Team FAO Agricultural Development Economics Division, Agricultural Development Economics (ESA) The Food and Agriculture Organization of the United Nations Rome, Italy. Rome, FAO. https://doi.org/10.1016/S0264-8377(03)00047-4

Benincasa, P., Guiducci, M., Tei, F., 2011. The nitrogen use efficiency: Meaning and sources of variation-case studies on three vegetable crops in central Italy. HortTechnology 21, 266–273. https://doi.org/10.21273/HORTTECH.21.3.266

Bregnballe, J., 2015. A Guide to Recirculation Aquaculture. An introduction to the new environmentally friendly and highly productive closed fi sh farming systems, 2015 Editi. ed. FAO and EUROFISH.

Chabite, I.T., Lei, Z., Ningning, Y., Qiang, F., Haiye, Y., 2017. Mode of Managing Nutrient Solution Based on N Use Efficiency for Lettuce (*Lactuca sativa* L.). J. Food Sci. Eng. 7, 29–37. https://doi.org/10.17265/2159-5828/2017.01.003

517   Ciolkosz, D.E.E., Albright, L.D.L., Both, A.J.J., 1998. Characterizing evapotranspiration in a greenhouse

518   lettuce crop. Acta Hortic. 255–262. https://doi.org/10.17660/ActaHortic.1998.456.29

519   EU. 2018. Communication from the commission to the european parliament, the council, the european

520   economic and social committee and the committee of the regions a sustainable Bioeconomy for Europe:

521   Strengthening the connection between economy, society and the environment

522   Conversa, G., Santamaria, P., Gonnella, M., 2004. Growth, yield, and mineral content of butterhead lettuce

523   (*Lactuca sativa* var. capitata) grown in NFT. Acta Hortic. 659, 621–628.

524   https://doi.org/10.17660/ActaHortic.2004.659.80

525   De Costa, W.., Ariyawansha, B., 1996. Effects of water stress on water use efficiency of different varieties of

526   common bean *(Phaseolus vulgaris L.)*. J. Natl. Sci. Counc. Sri Lanka 24, 253–266.

527   https://doi.org/http://dx.doi.org/10.4038/jnsfsr.v24i4.5558

528   Delaide, B., Goddek, S., Gott, J., Soyeurt, H., Jijakli, M.H., 2016. Lettuce (*Lactuca sativa* L. var. Sucrine)

529   growth performance in complemented aquaponic solution outperforms hydroponics. Water 8, 1–11.

530   https://doi.org/10.3390/w8100467

531   El Sayed, G.K., Samir, A.A., 2015. Effect of Flow Rate and Length of Gully on Lettuce Plants in Aquaponic

532   and Hydroponic Systems. J. Aquac. Res. Dev. 06, 6–10. https://doi.org/10.4172/2155-9546.1000318

533   Endut, A., Sultan, U., Abidin, Z., Lananan, F., Sultan, U., Abidin, Z., Hajar, S., Hamid, A., Sultan, U., Abidin,

534   Z., Jusoh, A., Autonomous, I., View, A.W., 2016. Balancing of nutrient uptake by water spinach *(Ipomoea*

535   *aquatica)* and mustard green *(Brassica juncea)* with nutrient production by African catfish *(Clarias*

536   *gariepinus)* in scaling aquaponic recirculation system. Desalin Water Treat 57–70.

537   https://doi.org/10.1080/19443994.2016.1184593

538   Espinosa Moya, E., Angel Sahagún, C., Mendoza Carrillo, J., Albertos Alpuche, P., Álvarez-González, C.,

539   Martínez-Yáñez, R., 2017. Herbaceous plants as part of biological filter for aquaponics system. Aquac Res

540   47, 1716–1726.

541   Eurofish, 2009. A Handbook for Sustainable Aquaculture: A Product of SustainAqua, Project No. ed. Eurofish

542   International Organisation, Copenhagen.

26

543 Fallovo, C., Rouphael, Y., Cardarelli, M., Rea, E., Battistelli, A., Colla, G., 2009. Yield and quality of leafy
544   lettuce in response to nutrient solution composition and growing season. J. Food, Agric. Environ. 7, 456–
545   462.

546 FAO, 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals.
547   Rome. Licence: CC BY-NC-SA 3.0 IGO.

548 FAO, 2016. Achieving Blue Growth, FAO. https://doi.org/10.1007/978-3-319-63498-2

549 Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K.V., Jijakli, H., Thorarinsdottir, R., 2015.
550   Challenges of sustainable and commercial aquaponics. Sustain. 7, 4199–4224.
551   https://doi.org/10.3390/su7044199

552 Hunt, R., Warren Wilson, J., Hand, D.W., Sweeney, D. G., 1984. Integrated Analysis of Growth and Light
553   Interception in Winter Lettuce I. Analytical Methods and Environmental Influences. Ann Bot 54, 743–757.
554   https://doi.org/10.1093/oxfordjournals.aob.a086847

555

556 Hyland, W., Wexler, A., 1983. Formulations for the thermodynamic properties of dry air from 173.15 K to
557   473.15 K, and of saturated moist air from 173.15 K to 372.15 K, at pressures to 5 MPa. ASHRAE Trans.
558   89, 520–535.

559 Johnson, G.E., Buzby, K.M., Semmens, K.J., Holaskova, I., Waterland, N.L., 2017. Evaluation of Lettuce
560   Between Spring Water, Hydroponic, and Flow-through Aquaponic Systems. Int. J. Veg. Sci. 23, 456–470.
561   https://doi.org/10.1080/19315260.2017.1319888

562 M'Hamdi, M., Boughattas, I., Chikh Rouhou, H., Souhli, E., Bettaieb, T., 2014. Effect of different levels of
563   nitrogen fertilizer on morphological and physiological parameters and nitrates accumulation of lettuce
564   cultivars (*Lactuca sativa L.*). Res Plant Biol 4(4), 27-38.

565 Mahlangu, R.I.S., Maboko, M.M., Sivakumar, D., Soundy, P., Jifon, J., 2016. Lettuce (Lactuca sativa L.)
566   growth, yield and quality response to nitrogen fertilization in a non-circulating hydroponic system. J. Plant
567   Nutr. 39, 1766–1775. https://doi.org/10.1080/01904167.2016.1187739

568   Mallick, F.R., Rahman, M.F., 2005. Proceedings of the International Conference & Exhibition on Soilless

569   Culture: ICESC-2005: Fort Canning Gallery, Singapore: September 5-8, 2005, in: Acta Horticulturae.

570   ISHS.

571   Martins, C.I.M., Eding, E.H., Verdegem, M.C.J., Schneider, O., Heinsbroek, L.T.N., Blancheton, J.P.,

572   D'Orbcastel, E.R., Verreth, J.A.J., 2010. New developments in recirculating aquaculture systems in Europe:

573   A perspective on environmental sustainability. Aquac. Eng. 43, 83–93.

574   https://doi.org/10.1016/j.aquaeng.2010.09.002

575   Nozzi, V., Graber, A., Schmautz, Z., Mathis, A., Junge, R., 2018. Nutrient Management in Aquaponics:

576   Comparison of Three Approaches for Cultivating Lettuce, Mint and Mushroom Herb. Agronomy 8, 27.

577   https://doi.org/10.3390/agronomy8030027

578   Pantanella, E., Cardarelli, M., Colla, G., Rea, E., Marcucci, A., 2012. Aquaponics vs. Hydroponics: Production

579   and Quality of Lettuce Crop. Acta Hortic. 927, 887–894.

580   https://doi.org/10.17660/ActaHortic.2012.927.109

581   Pignata, G., Casale, M., Nicola, S., 2017. Water and nutrient supply in horticultural crops grown in soilless

582   culture; resource efficiency in dynamic and intensive systems, in: Tei F., Nicola S., Benincasa P. (Eds.),

583   Advances in Research on Fertilization Management of Vegetable Crops. Springer, Cham, Berlin, Germany,

584   pp. 183–219

585

586   Qiansheng, L., Xiaoqiang, L., Bin, T., Mengmeng G., 2018. Growth Responses and Root Characteristics of

587   Lettuce Grown in Aeroponics, Hydroponics, and Substrate Culture. Horticulturae 4, 35.

588   https://doi:10.3390/horticulturae4040035

589   Rakocy, J., Bailey, D., Shultz, R., Danaher, J., 2007. Preliminary Evaluation of Organic Waste from Two

590   Aquaculture Systems as a Source of Inorganic Nutrients for Hydroponics. Acta Hortic. 742, 201–207.

591   https://doi.org/10.1002/9783527693535.ch14

592   Rakocy, J.E., Masser, M.P., Losordo, T.M., 2006. Recirculating Aquaculture Tank Production Systems :

593   Aquaponics — Integrating Fish and Plant Culture. SRAC Publ. 454.

594 Savvas, D., Passam, H..C., Olympios, C., Nasi, E., Moustaka, E., Mantzos, N., Barouchas, P., 2006. Effects of

595 Ammonium Nitrogen on Lettuce Grown on Pumice in a Closed Hydroponic System. HortSci, 41(7), 1667-

596 1673. https://doi.org/10.21273/HORTSCI.41.7.1667

597 Scuderi, D., Giuffrida, F., Noto, G., 2009. Effects of Nutrient Solution EC on Yield, Quality and Shelf-Life of

598 Lettuce Grown in Floating System. Acta Hortic. 807, 221–226.

599 https://doi.org/10.17660/ActaHortic.2009.807.77

600 Shaban N.T., Tzvetkova N., Cherkez R., Parvanova P., 2016. Evaluation of response of lettuce (*Lactuca sativa*

601 *L.)* to temperature and light stress. Acta Agrobot. 69, 1 – 9. http://dx.doi.org/10.5586/aa.1664

602 Shi, L., Wang, Y., Zhang, L., Wang, P., Desalination, W., 2017. (Supporting infomation for) Rational design

603 of a bi-layered reduced graphene oxide film on polystyrene foam for solar-driven interfacial water

604 evaporation. J. Mater. Chem. 5, 16212–16219.

605 Smith, B.J., Phillips, G.M., Sweeney, M., 2014. Environmental Science, 1st Edition

606 Stefanelli, D., Winkler, S., Jones, R., 2011. Reduced nitrogen availability during growth improves quality in

607 red oak lettuce leaves by minimizing nitrate content, and increasing antioxidant capacity and leaf mineral

608 content. Agric. Sci. 02, 477–486. https://doi.org/10.4236/as.2011.24061

609 Timmons, M., Ebeling, J., 2007. Recirculating aquaculture, Cayuga Aqua Ventures LLC. Itaca, NY, USA. 948

610 pp.

611 Trejo-Téllez I.L., Gómez-Merino, F.C., 2012. Nutrient Solutions for Hydroponic Systems, in: Asao, T., (Ed),

612 Hydroponics - A Standard Methodology for Plant Biological Researches. InTech, Rijeka, Croatia, pp. 1-

613 22, https://doi:10.5772/37578

614 Tzortzakis, N.G., 2009. Alleviation of salinity-induced stress in lettuce growth by potassium sulphate using

615 nutrient film technique. Int. J. Veg. Sci. 15, 226–239. https://doi.org/10.1080/19315260902751320

616 Ünlükara, A., Cemek, B., Karaman, S., Erşahin, S., 2008. Response of lettuce (*Lactuca sativa* var. Crispa) to

617 salinity of irrigation water. New Zeal. J. Crop Hortic. Sci. 36, 265–273.

618 https://doi.org/10.1080/01140670809510243

619 Verdegem, M., Bosma, R., Verreth, J., 2006. Reducing Water Use for Animal Production Through
620   Aquaculture. Journal, Int. Dev. Water Resour. 22, 101–113. https://doi.org/10.1080/07900620500405544

621 Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., Van Vliet, M.T.H.,
622   Yillia, P., Ringler, C., Burek, P., Wiberg, D., 2016. Modeling global water use for the 21st century: The
623   Water Futures and Solutions (WFaS) initiative and its approaches. Geosci. Model Dev. 9, 175–222.
624   https://doi.org/10.5194/gmd-9-175-2016

625 Wielgosz, Z.J., Anderson, T.S., Timmons, M.B., 2017. Microbial Effects on the Production of Aquaponically
626   Grown Lettuce. Horticulturae 3, 46. https://doi.org/10.3390/horticulturae3030046

627 Zhang, J., Ren, W., An, P., Pan, Z., Wang, L., Dong, Z., He, D., Yang, J., Pan, S., Tian, H., 2015. Responses
628   of Crop Water Use Efficiency to Climate Change and Agronomic Measures in the Semiarid Area of
629   Northern China. PLoS One 10, e0137409. https://doi: 10.1371/journal.pone.0137409

630 Żmijewski, T., Kowalska, A., Jankowska, B., Ulikowski, D., Zakęś, Z., Zak, Z., Zmijewski, T., Ulikowski, D.,
631   Kowalska, A., 2006. Slaughter value and flesh characteristics of European catfish (*Silurus glanis*) fed
632   natural and formulated feed under different rearing conditions. Eur. Food Res. Technol. 224, 453–459.
633   https://doi.org/10.1007/s00217-006-0349-2

634

635