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Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics

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ABSTRACT

Aquaponics for intensive crop production is a highly complex system in which three different biological systems (fish, plants, and nitrifying bacteria) with different requirements must be merged. Finding the right combination is a serious challenge and the dependencies avoid a high productivity until now. Therefore, a unique and innovative double recirculating aquaponic system (DRAPS) was developed as a prerequisite for a high productivity comparable to professional stand-alone fish/plant facilities. It consists of two independent recirculating units – a recirculating aquaculture unit for fish production and a closed hydroponic cycle for plant production – which were connected unidirectional. This allows the use of fish waste water as nutrient supply for plants in hydroponics and its optimisation for plant growth by fertilizer supply without negative effects on fish rearing. Furthermore it allows a sustainable food production.

In a new constructed DRAPS research facility, first investigations with tilapia and tomato production were conducted in 2015. During an annual production, it was demonstrated that in DRAPS comparable tomato yields were produced as obtained for conventional hydroponics. Even fruit parameters such as contents of lycopene and ß-carotene resulted in the same quantity when both systems were compared. Furthermore, the fertilizer use efficiency was increased by 23.6% in favour of the DRAPS. The total fresh water use efficiency was also increased using aquaponics.

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1. Introduction

The world is confronted with the challenges of the 21st century including an increase in the world population, which is linked to a high demand of energy, food and water. These circumstances lead to climate changes, water and fossil fuel scarcities, soil degradation and food shortage. To face these challenges, sustainable food production with less water and energy consumption is becoming more and more important.

The FAO (2014) reported that aquaculture is one of the fastest-growing food production sectors and provides already around 50% of all fish and fish products for human consumption. Additionally, a further intensification of aquaculture and an associated higher fish production is forecasted for the future. But intensive production systems are generally accompanied by drawbacks. Traditional aquaculture production in natural ponds or race-ways causes sig-

Abbreviations: %, percentage; °C, degree centigrade; 3-cp, 3-chamber pit; B, boron; BER, blossom end rot; Ca, calcium; CFA, continuous flow analysis; cm, centimetre; CO_2, carbon dioxide; Cu, copper; DI, distilled; DM, dry matter; DRAPS, double recirculating aquaponic system; dS, deci siemens; EC, electric conductivity; Fe, iron; FUE, total fertilizer use efficiency; FWUE, total fresh water use efficiency; HCl, hydrochloric acid; ICP-OES, inductively coupled plasma-optical emission spectrometry; K, potassium; kg, kilogram; L, litre; LA, leaf area; m, metre; m^2, square metre; m^3, cubic metre; Mg, magnesium; mg, milligram; min, minute; mL, millilitre; Mn, manganese; Mo, molybdenum; N, nitrogen; Na, sodium; NCDs, chronic non-communicable diseases; NH_4^+, ammonium; NH_4-N, ammonium nitrogen; NH_4NO_3, ammonium nitrate; NO_2^-, nitrite; NO_3^-, nitrate; NO_3-N, nitrate nitrogen; P, phosphorus; RAS, recirculating aquaculture systems; S, sulphur; SAR, sugar-acid ratio; SRAPS, single recirculating aquaponic system; SSC, soluble solids content; TA, titratable acid; Zn, zinc.

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nificant negative environmental impacts, for example, the use of high amounts of fresh water and the hazard that a high nutrient load in the waste water can influence the environment negatively. Approaches to solve these drawbacks are recirculating aquaculture systems (RAS). These use 90–99% less fresh water than conventional systems and the nutrient release to the environment is accordingly reduced (Timmons et al., 2010; Verdegem, 2013).

Nevertheless, even RAS reduces the fresh water demand, a certain amount of fresh water is needed and the waste water is heavily accumulated by undesirable nutrients, especially of nitrogen. Aquaponics is an approach to minimise these negative impacts on the environment caused by RAS. Aquaponics consists of a combination of intensive fish production in pond culture and plant production in a hydroponic system (Klinger and Naylor, 2012). The additional production of plants may increase the added value and the sustainability of food production. The basic concept of this combined farming system is its use as a single recirculating aquaponic system (SRAPS), in which the waste water from fish production becomes available for plant production. The water is cleaned by the plants and bacteria living in the rooting zone and can afterwards be reused for fish production. This means that the fish waste water flows into the hydroponic plant production system, passes the rooting zone of the plants and subsequently flows back into the fish rearing tanks. The technical composition of aquaponic systems, including a biofilter and/or a mechanical filter, can differ from system to system and is well documented by Diver and Rinehart (2010) and Rakocy et al. (2006). As such, aquaponics could relieve the environment by the double use of water and nutrients and increase the profit by producing two cash crops (Diver and Rinehart, 2010; Rakocy et al., 2006; Tyson et al., 2011). SRAPS have to struggle with different technical challenges (Goddek et al., 2015), because it is a highly complex system where three different biological systems (fish, plants, and nitrifying bacteria) must be merged into one working system. This difficulty prevents a high productivity, especially for fruit vegetables (Goddek et al., 2015; Vergote and Vermeulen, 2010; Wortman, 2015). In this context, one of the most critical points is the different pH optimum for fish, plants and nitrificants. While the pH optimum for fish and nitrifying bacteria ranged between 7 and 9 (Hochheimer and Wheaton, 1998; Rakocy et al., 2006), the recommended pH value for optimal nutrient availability in hydroponics varied between 5.5 and 6.5 (Hochmuth, 2001). If SRAPS are optimised, for example, for fish and bacteria (pH > 7), the availability of phosphorus, zinc, iron, manganese, copper and boron can be limited for plants (Hochmuth, 2001; Rakocy et al., 2006). For example, plants, such as rice, cassava, maize and French bean, are sensitive to high pH levels (>5.6–6.5) (Alam, 1981; Islam et al., 1980). Another crucial point arises from different nutrient requirements for fish and plants. The main input of nutrients in SRAPS is fish feed and consequently not only the nutrient source for the fish, but also, indirectly, for the plants as well. Nevertheless, a deficit of nutrients for plants is predictable when these would not be added to the hydroponic unit. Potassium, for example, has to be adjusted for plant production because the concentration released by the fish is not sufficient for plant growth. But also iron, calcium and phosphorus are usually insufficient in aquaponics and must be adjusted (Goddek et al., 2015; Rakocy et al., 2004, 2006; Savidov et al., 2005).

SRAPS with combined production of tilapia and lettuce in raft systems seems to be well established (Tyson et al., 2011). Pantanella et al. (2012) have produced similar lettuce yields in aquaponics and hydroponics, but the yields were mainly dependent on the fish stocking density and nutrients were supplemented into the aquaponics. However, many growth parameters of mint and basil were negatively influenced by aquaponics (Roosta, 2014). Similar applies to tomato yields, which were significantly lower in aquaponics than those produced in hydroponics (Graber and Junge, 2009). Considering the latter investigation, very little is known about comparisons of intensive crop production in aquaponics and hydroponics under the same conditions (Nichols and Savidov, 2011). Tyson et al. (2011) suggested more long-term research, because the lack of information about factors of success is one reason why the most of aquaponic systems are only used as hobby or for education and not for commercial production (Love et al., 2014).

One approach to solve the mentioned problems caused by SRAPS was taken by Kloas et al. (2015). They have developed a unique and completely new double recirculating aquaponic system (DRAPS). The DRAPS addresses the challenge to achieve the food supply for the growing world population by intensive large-scale food production. To get an overview, the main advantages and disadvantages of SRAPS and DRAPS are listed in Table 1. One key advantage of DRAPS is the separation of the fish and plant cycle (Fig. 1). As such, both production units are independent of each other. This means that the water quality, especially nutrients and the pH value, can be adapted to optimal conditions in both cycles separately. This improvement allows intensive production of fish and plants as in aquaculture and hydroponics, respectively. However, the construction, the fish water to plant ratio and the adjustment of the nutrient solution are not optimised (Kloas et al., 2015) and only few scientific studies exist about this technique.

Therefore, as a first step, the present study was focused on the optimisation of DRAPS. This include the installation of a 3-champer pit as part of the system, a spatial separation of fish and plant production, a reduced fish to plant ratio and the continuously adjustment of the nutrient solution applied for plants, in order to achieve equal amounts of tomatoes as generated in intensive crop production using hydroponics. The development and productivity of tomato plants grown under DRAPS conditions were compared with hydroponically produced ones.

Additionally, external and internal fruit quality parameters, such as blossom end rot fruit and contents of carotenoids, soluble solids and the sugar-acid ratio were analysed in tomatoes as well. These investigations were absolutely necessary because very little is known about fruit quality parameters caused by aquaponics. To demonstrate how sustainable DRAPS are working the fertilizer use and the total fresh water use efficiency were calculated and compared to that caused by conventional hydroponics. The optimal fish water to plant ratio was verified as well. Based on all results, first recommendations for successful intensive crop production using DRAPS are discussed.

2. Material and methods

2.1. System design

The DRAPS used in the present study is based on the technology developed by Kloas et al. (2015). The experiments were carried out in a new constructed research aquaponic facility located in Abtshagen, Germany (52°31′12.025″N, 13°24′17.834″E). The total area was 196 m^2, which was divided into three areas: (i) technical room (14 m^2); (ii) the fish farm based on RAS (43 m^2); (iii) a Venlo-type greenhouse (139 m^2). The computer control system and a cogeneration unit were placed in the technical room. The RAS contained four identical glass fibre fish tanks with a total net production volume of 7.2 m^3. The water was cleaned by a mechanical filter (glass fibre sedimentation tank) with a volume of 1.3 m^3 and the effluent was collected in a pump sump with a volume of 2.34 m^3. From the pump sump the water was pumped to a trickling biofilter for nitrification to convert ammonium into nitrate. The specific surface area of the filter bodies was 120 m^2 m^{-3}. The nitrified water was collected in a reception water tank (0.4 m^3) and flowed back to the fish rearing tanks. The total volume of the whole RAS was around

Table 1
Advantages and disadvantages of single recirculating aquaponic systems (SRAPS) and double recirculating aquaponic systems (DRAPS).

Aquaponic system	Current advantages and aisadvantages	References
SRAPS	Advantages	
	• combined production of lettuce and tilapia is well established	Tyson et al. (2011)
	• well suited for hobby and education	Love et al. (2014)
	Disadvantages	
	• suboptimal conditions for all integrated species, such as fish, bacteria and plants, in terms of pH, nutrients, water quality	Goddek et al. (2015)
	• low production, especially on plant side	Goddek et al. (2015)
	• too less scientifically research on direct comparison of aquaponics and single production of fish or plants	Nichols and Savidov (2011)
	• too little long term research	Tyson et al. (2011)
	• not used for commercial production	Love et al. (2014)
DRAPS	Advantages	
	• separation of fish and plant production enables optimal production conditions (pH, nutrients, water quality) for both, fish and plants	Kloas et al. (2015)
	• optimisation measures in plant cycle does not affect fish cycle	Kloas et al. (2015)
	• allows intensive crop production in large a scale	Kloas et al. (2015)
	Disadvantages	
	• non-optimised construction, fish water to plant ratio, and adjustment of the nutrient solution	Kloas et al. (2015)
	• too less scientific research	

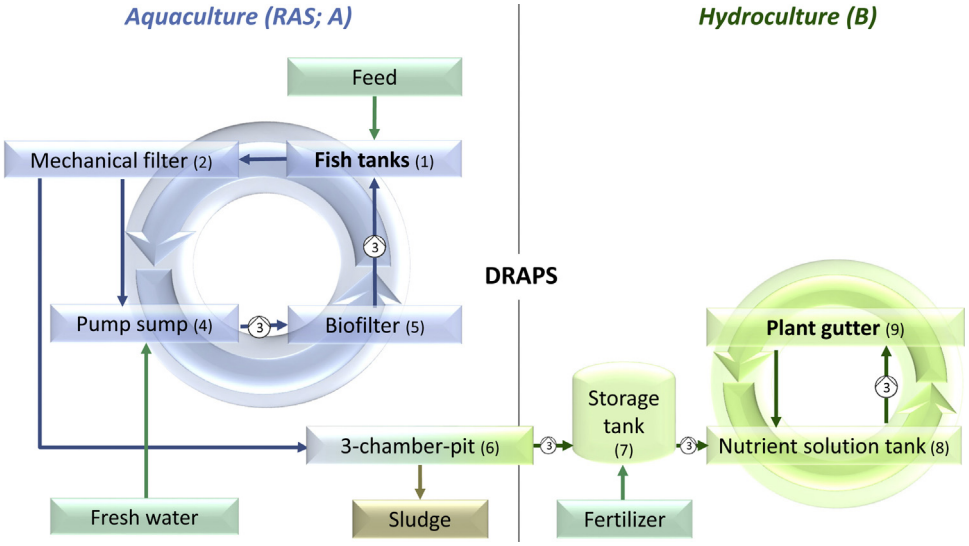

Fig. 1. Schematic diagram of the used double recirculating aquaponic system (DRAPS). The recirculating aquaculture system (RAS; A): fish-rearing tanks (1), mechanical filter (sedimentation) (2), pump system (3) and trickling biofilter (5) and pump sump (4). Recirculating hydroponic unit (B): nutrient solution tanks (8) and plant gutters (9). Both systems are connected via a 3-chamber-pit (3-cp; 6).

12 m^3. Depending on the water quality and the fish stocking density, water treated with the mechanical filter was removed one to three times a week into the 3-chamber pit (3-cp; 4.5 m^3) (Fig. 1). The fish water removing occurred unidirectional and discontinuously. From the 3-cp it was pumped into the storage tank (1 m^3) implemented in the greenhouse and was kept there until its use for hydroponically plant production (Fig. 1). Before the fish waste water was delivered to the plants, it was adjusted in the nutrient solution tank using mineral fertilizer to provide optimal nutrient concentrations for plant growth.

The greenhouse had a standing wall height of 4.2 m, which was equipped with double glass plates, whereas the roof was covered with single glass plates. The internal construction consisted of two single and two double gullies. Each double gully was restricted by a single gully, which was placed on the left or right outer wall, respectively. To evaluate plant characteristics, only the double gullies were considered. At the end of each gully, a nutrient solution tank with a volume of 300 L was installed. The cultivation method was based on nutrient film technique (NFT) applied in a recirculating system, in which the water was constantly pumped with a flow rate of 9 L min^{-1} for 24 h per day. The greenhouse was heated by a conventional floor level pipe heating system. Furthermore, a single layer energy screen and twelve high-pressure vapour sodium lamps were installed in the greenhouse.

2.2. Investigational set up

The experiments were conducted from 23.01.2015 until 08.01.2016. During this time, a combination of tilapia (*Oreochromis niloticus*) and tomatoes (*Solanum lycopersicum* L., cv. Pureza) were produced.

2.2.1. Fish production

The RAS was stocked with Red Natural Male Tilapia on 23.1.2015, 12.3.2015, and 15.7.2015. The initial stocking densities ranged between 2.0 and 2.3 kg m^{-3}. All batches were sorted once per growth period to separate bigger and smaller fish. The stocking densities during the whole fish production fluctuated between 2.0 kg m^{-3} and a maximum of 39.1 kg m^{-3}. During the investigations, the mean stocking density (20.7 kg m^{-3}) was kept low, because the fish batches were added and harvested stepwise. Other reasons for this practice were the activation of the biofilter, the fish feed, which changed in between to find an optimum, and some adjustments of the construction parts within the research plant during the growth period. All these factors mean stress for fish and led to suboptimal stocking densities. The feeding rate was between 0.7% and 2.4% and the daily water exchange rate in the RAS was 6.3% of the net fish production volume of 7.2 m^3. The whole fish production period was 351 days.

2.2.2. Plant growth conditions

During February until April, the set-points of the heating system were defined as 22 °C and 18 °C for day and night, respectively, and the ventilation was opened at 26 °C to cool the greenhouse. From mid of April until October the set-point for the heating system was changed to 17 °C for day and night and the set point for ventilation was dropped down to 21 °C. The energy screen was closed from one hour after sunset to one hour before sunrise and opened stepwise. The stepwise opening was controlled by a maximum temperature difference of two degree centigrade between roof and remaining greenhouse region. Between 7 a.m. and 8 p.m. the artificial light started at a level below 20 W m^{-2} global radiations.

For the experiments a net-acreage of 62.6 m^2 was planted with 144 tomato plants (2.3 plants per square metre). 48 plants per treatment were cultivated in two gullies. The plants were planted at 22.01.2015 when the first truss was visible. Two different treatments with two gullies each were applied. As such, one nutrient solution was mixed with fresh water and the other one with fish waste water referred to as hydroponics and aquaponics, respectively. The aquaponics treatment is shown schematically in Fig. 1. The first application of fish waste water as process water to mix the nutrient solution was started at 05.02.2015. In this context, both nutrient solutions were adjusted with mineral fertilizer to an EC (electric conductivity) of 1.8 dS m^{-1} in order to achieve optimal growth conditions for tomatoes. To provide an optimal nutrient concentration, the nutrient content of both treatments was analysed periodically once a week. The target nutrient concentration was composed as follows: 151 mg L^{-1} nitrogen (N), 37 mg L^{-1} phosphorus (P), 234 mg L^{-1} potassium (K), 128 mg L^{-1} calcium (Ca), 24 mg L^{-1} magnesium (Mg), 110 mg L^{-1} sulphur (S), 2.0 mg L^{-1} iron (Fe), 0.3 mg L^{-1}boron (B), 0.2 mg L^{-1} copper (Cu), 1.2 mg L^{-1} manganese (Mn), 0.05 mg L^{-1} molybdenum (Mo) and 0.4 mg L^{-1} zinc (Zn) (Lattauschke, 2004).

2.3. Determination of plant yield and plant growth

From 14.04.2015 until 27.10.2015 the tomato fruits were harvested once a week. To compare the total yield, the harvested tomatoes (n = 48) of each plant were weighed and counted. The fruit quality of ten plants per treatment (n = 10) were evaluated by categorizing the fruits into marketable fruits and non-marketable fruits. Latter were defined as fruit affected by blossom end rot (BER). The yield of both weight classes related to the total yield of the respective plant was used to calculate the yield percentage of both weight classes. Afterwards, the results were extrapolated on the canopy and expressed as kg cumulative yields per m^2 at the end of the experiments.

On four plants per treatment the number of leaves were counted and the leaf area (LA) per plant was calculated in three consecutive weeks in August 2015, in order to obtain results based on three biological repetitions (n = 12). For LA, the length and width of all leaves per plant (leaves > 20 cm) were measured with a folding rule. To calculate the leaf area, the data were integrated in an exponential function (1) developed by Dannehl et al. (2015a). At the end of the tomato production the total plant lengths of 6 plants per treatment were measured.

$$LA = \frac{13.781 * e^{(0.075 * leaflength)} + 293.381 * e^{(0.027 * leafwidth)}}{2} - 164.809 \quad (1)$$

2.4. Non-destructively method to determine leaf chlorophyll content

On four dates from June to August 2015, the remittance spectra of leaves were measured. As such, a hand held photodiode array spectrophotometer (Pigment Analyzer PA-1101, CP, Falkensee, Germany) was used to record the leaf spectra in the UV and visible wavelength range from 401 to 1048 nm (MMS1 UV–vis, Carl Zeiss, Jena, Germany). The measurement was carried out on three positions at the first fully developed leaf of each plant (n = 192). The remittance was evaluated at 750 (R_{770}) and 705 (R_{705}) nm to calculate the Chl NDI = Chl NDI = $(R_{750} - R_{705})/(R_{750} + R_{705})$ (Gitelson and Merzlyak, 1994; Richardson et al., 2002).

2.5. Sampling and preparation for chemical analyses of tomatoes

To determine the titratable acid (TA), the soluble solids content (SSC), as well as the content of carotenoids (ß-carotene and lycopene), three replicates per treatment containing five fruit each (>70 g) were randomly harvested. The sampling was repeated in three consecutive weeks in August 2015 in order to compare three biological repetitions (n = 9). The fruit were harvested at a ripening stage 9 (according to Organization for Economic Co-operation and Development (OECD) colour gauge) from trusses formed in the same height in the canopy. After harvesting, the fruit were frozen with liquid nitrogen and stored at −20 °C. Before chemical analyses were performed, the fruit were quartered. Two quarters were used to determine the dry matter (DM) content, whereas the rest of the fruit were mixed to a homogenate (KenwoodHB856, De'LonghiDeutschland GmbH, Neu-Isenburg; Germany).

2.5.1. Titratable acid, soluble solids and sugar-acid ratio

According to ASU (1983) the TA in the homogenate was determined by potentiometric titration. The exact procedure is described by Dannehl et al. (2014b).

For the determination of the SSC, 1.5 millilitre (mL) of the homogenate were filled into a 2 mL Eppendorf tube (Eppendorf Tubes®,2 mL Eppendorf; Hamburg, Germany) and centrifuged at 6000 rpm for 5 min. After calibration with distilled (DI) water, the supernatant was measured using a digital refractometer (PR101, ATAGO; Karlsruhe, Germany). The refractometer detects reducing sugars and other soluble solids as °BRIX. One °BRIX is equivalent to 1 g soluble solids per 100 g fresh weight (g 100 g^{-1} FW). By dividing the content of SCC by the content of TA the sugar-acid ratio (SAR) was calculated.

2.5.2. Carotenoids

The extraction of lycopene and ß-carotene was conducted according to the method of Fish et al. (2002), which is based on hexane as solvent. The extraction and measurement is exactly described by Dannehl et al. (2014a). All measurements were carried out in duplicate and the content of carotenoids was calculated according to Nagata and Yamashita (1992). The results were expressed as milligram per g DM (mg g^{-1} DM).

2.6. Sampling and preparation for chemical analyses of nutrients in nutrient solutions

The samples to analyse the nutrients in the fish waste water and used nutrient solutions were taken from the storage tank (Fig. 1, No. 7) and respective nutrient solution once a week (05.02.–20.10.2015) and stored in a freezer at −20 °C. After defrosting, the samples were filtrated and afterwards directly analysed using inductively coupled plasma-optical emission spectrometry

(ICP-OES; P, K, Ca, Mg, S, and Na) and continuous flow analysis (CFA; ammonia nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N))

2.6.1. Nutrients in water samples

The nutrient analyses were conducted by ICP-OES (iCAP 6300 Duo MFC, Fa. Thermo; Waltham, USA). Around 15 mL of the filtrated solution were used to flush the ICP. Afterwards, around 45 mL of the sample was used for measuring. The calibration curves for ICP-OES were established with the following reference solutions: blank 1.4 mol L^{-1} HNO_3; 0–100 mg L^{-1} of P; 0–300 mg L^{-1} of K; 1–300 mg L^{-1} of Ca; 0–100 mg L^{-1} of Mg; 0–50 mg L^{-1} of S and 0–100 mg L^{-1} of Na. Additionally to the reported wavelength by Dannehl et al. (2015b) Na were analysed at wavelength 589.9 nm. The particular elements in the digestion solutions were analysed in duplicate and results were expressed as mg per litre (mg L^{-1}).

2.6.2. Nitrogen in water samples

The nitrogen content in the water samples were analysed using CFA (San^{++}, Fa. SKALAR; Breda, Netherlands). The used reference solutions were 0.584 mg L^{-1} NH_4^+ (Ammonium standard solution, Merck KGaA; Darmstadt, Germany) and 0.565 mg L^{-1} NO_3^- (Nitrate standard solution, Merck KGaA; Darmstadt, Germany). The standard series for CFA were established with dissolved NH_4NO_3 in the following concentrations: 0.25 mg L^{-1}, 0.5 mg L^{-1}, 1.0 mg L^{-1}, 2.0 mg L^{-1} and 3.0 mg L^{-1}. As rinse solution for the auto sampler, calcium chloride was used. As working solutions for NH_4-N analysis, one buffer solution (66 g potassium sodium tatrate + 48 g sodium citrate trihydrate + 6 mL Brij (30%) in 2 L DI water) and other solutions such as sodium salicylate (12.5 g NaOH + 40 g sodium salicylate in 0.5 L DI water), sodium nitroprusside (0.5 g in 0.5 L DI water) and sodium dichloroisocyanurate (1.0 g in 0.5 L DI water) were used. For analysis, NH_4-N was chlorinated to monochloramine. Latter react with salicylate to 5-aminosalycilate. After oxidation and coupling reaction, a green colour complex was formed. The adsorption of this colour complex was measured at a wavelength of 660 nm. For NO_3-N analysis, a buffer solution (3.405 g imidazole diluted in HCl + 3 mL Brij (30%) in 1 L DI water) and a staining reagent (50 mL H_3PO_4 + 5 g sulfanilamide + 0.25 g α-naphthylethylendiamindihydrochloride in 0.5 L DI water) were blended. For analysis, NO_3-N was reduced to NO_2^- by a cadmium column. After NO_2^- reacted with sulfanilamide and coupled with α-naphthylethylendiamindihydrochloride, a red coloured azo dye was formed. This azo dye was colourimetrically measured at a wavelength of 540 nm.

NH_4-N and NO_3-N in the digestion solutions were analysed in duplicate and results were expressed as mg L^{-1}.

2.7. Calculation of total fresh water and fertilizer use and its efficiencies

2.7.1. Water and fertilizer use

A water metre was used to measure the fresh water volume consumed by the RAS system during the whole fish production period. The same procedure was used to measure the volume of fish waste water and the fresh water supplied to the respective plant treatment. Afterwards, the ratio from fish waste water to the fresh water supplied to the plants and the RAS, respectively, was calculated. The volume of the fresh water was further used to calculate the fresh water use efficiency of the control, described under Section 2.7.2.

To point out the fertilizer use, the amount of each nutrients added to the different treatments was weighed and summed until the end of the plant production. In these calculations, the loss of nutrients caused by regularly discarded volumes of nutrient solution used to prevent undesirable nutrient accumulation was not considered. The total fertilizer use is expressed in kilogram (kg). Fertilizer savings by aquaponics were calculated by using the amount of nutrient requirements in aquaponics in relation to that used in hydroponics, where the latter was given as 100%.

2.7.2. Fresh water and fertilizer use efficiency

The total fresh water use efficiency (FWUE) was calculated for both, the hydroponic and aquaponic system. In terms of the hydroponic system, the FWUE was calculated as ratio between marketable fruit and the total fresh water use. The results were expressed as kg tomatoes per m^3 fresh water (kg m^{-3}). However, the FWUE regarding the aquaponic system was calculated in the same manner, but under consideration of the total fresh water use for fish production in the RAS and fish waste water use for tomato production. As such, it was calculated how many kg fish and tomatoes can be produced with the same volume of fresh water.

The mean total fertilizer use efficiency (FUE) in terms of all nutrients for both treatments was calculated as a ratio between the total yield and the total fertilizer use (Brady et al., 2015) as described earlier. The results are expressed as kg total fruit yield per kg fertilizer supply (kg kg^{-1}).

2.8. Statistical analysis

The effect of nutrient solutions based on fish waste water and fresh water on plant parameters, such as yield, leaf area, number of leaves, Chl NDI, and on internal fruit quality parameters, such as contents of dry matter, SSC, SAR, lycopene and ß-carotene were analysed using SPSS package version 19.0. To compare the mentioned investigation parameters of both treatments, parametric *t*-tests were used after confirmed normal distribution by Kolmogorov-Smirnov test. Otherwise the non-parametric Mann-Whitney *U* Test was used. Mean values and standard deviations are displayed as numbers or bars in tables and figures, respectively. Statistical analyses were carried out on a significance level of $p < 0.05$, where significant differences between the treatments are characterised by small letters. Furthermore, the nutrients in the fish waste water and different nutrient solutions were calculated by the same software program and in the same manner as described before.

3. Results

3.1. Plant yield and plant growth

The use of fish waste water with additional mineral fertilizer resulted in similar yields as in conventional hydroponic production (Fig. 2). During the harvest period of 197 days, a total amount of 31.64 kg tomato fruit per m^2 was harvested in hydroponics, while in aquaponics was 29.38 kg m^{-2}, being not significant different. The rate of marketable fruit on total yield was nearly the same in both treatments (hydroponics = 99.1%, aquaponics = 99.5%). However, the production under aquaponic conditions resulted in a significant smaller rate (−0.37%) of fruit affected by blossom end rot (BER) compared to those ripened in hydroponics.

The plants grown under aquaponic conditions formed a significant smaller leaf area per plant (1.15 m^2) than those grown in hydroponics (1.36 m^2) (Table 2). However, the smaller leaf area in aquaponics was not accompanied by a lower number of leaves per plant. Furthermore the plant length did not show differences between the treatments (hydroponics = 10.8 m; aquaponics = 10.9 m). In contrast, the Chl NDI was increased by 17.9% in leaves developed by the influence of aquaponics compared to that in control leaves.

3.2. Primary and secondary metabolites

The analyses showed a significantly lower DM content (−5.6%), SSC (−7%) and SAR (−5.0%) in tomatoes ripened under the

Table 2
Effects of hydroponics and aquaponics on leaf area (n = 12), number of leaves (n = 12), plant length (n = 6), and Chl NDI* (n = 192) of the first fully developed tomato leaf.

Treatment	Leaf area per plant(m^2 $plant^{-1}$)	Number of leaves(Number $plant^{-1}$)	Plant length(m)	Chl NDI
Hydroponics	1.36 ± 0.15^b	21.0 ± 0.7^a	10.8 ± 0.46^a	0.56 ± 0.19^a
Aquaponics	1.15 ± 0.16^a	20.5 ± 1.3^a	10.9 ± 0.23^a	0.66 ± 0.16^b

The leaf area (LA), number of leaves (LN), plant length (PL) and remittance spectra indices Chl NDI content were compared using *t*-test (LA, PL) or Mann-Whitney U-Test (LN, Chl NDI), respectively. Data represent the mean of three (LA, LN) and four (Chl NDI) biological replicates ± standard deviation. Significant differences are indicated as small letters ($p < 0.05$).
* Chl NDI = Remittance (R) spectra indices for chlorophyll content.

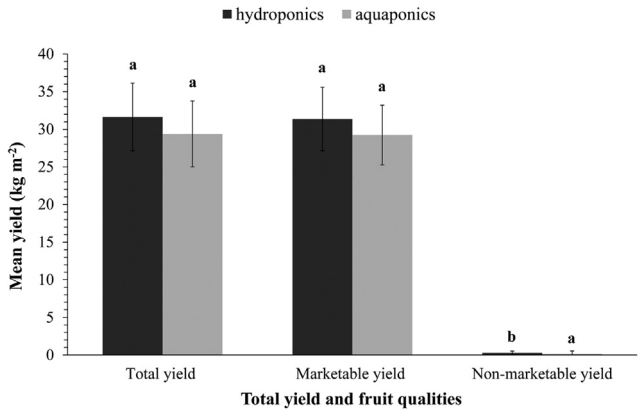

Fig. 2. Effects of hydroponics and aquaponics on fruit yield and quality. The values represent the mean value of total tomato yield, marketable fruit yield and non-marketable fruit yield (n = 48) produced within 28 weeks ± standard deviation. The mean yields were tested using *t*-test and Mann-Whitney *U* Test, respectively and small letters indicate significant differences.

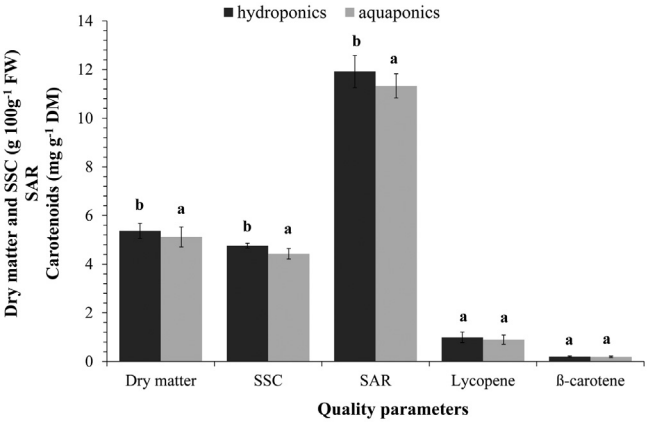

Fig. 3. Influence of fresh water (control) and fish waste water based nutrient solutions on fruit dry matter content, soluble solids content (SSC), sugar-acid ratio (SAR), as well as lycopene and ß-carotene content. The data represent mean values and ± standard deviation (n = 9). The analysed contents were compared using *t*-test and represent the mean of three repetitions in three consecutive weeks. Small letters indicate significant differences ($p < 0.05$).

influence of aquaponics compared to hydroponics (Fig. 3). The carotenoid content in terms of lycopene (hydroponics = 0.99 mg g^{-1} DM, aquaponics = 0.90 mg g^{-1} DM) and ß-carotene (hydroponics = 0.20 mg g^{-1} DM, aquaponics = 0.19 mg g^{-1} DM) did not differ significantly between both treatments.

3.3. Nutrients in pure fish waste water, as well as in fresh and fish waste water based nutrient solutions

The amount of nutrients in the fish waste water used for plant production fluctuated strongly during the whole fish production period (Table 3). After passing a 3-chamber pit, its

Table 3
Nutrients in pure fish waste water, as well as in nutrient solutions based on mixture of fresh and fish waste water, respectively.

Element	Pure* fish waste water		Nutrient solution based on** fresh water	Nutrient solution based on** fish waste water
	Mean (mg L^{-1})	min.–max. (mg L^{-1})	Mean (mg L^{-1})	Mean (mg L^{-1})
NH_4-N	24.2 ± 20.8	0.05–64.1	0.7 ± 0.9^a	7.0 ± 9.0^a
NO_3-N	14.6 ± 13.9	bld***–42.7	111.3 ± 19.4^a	157.0 ± 50.3^b
P	8.0 ± 5.0	0.06–15.8	67.2 ± 34.9^a	204.9 ± 24.5^b
K	30.2 ± 16.7	3.2–69.1	60.0 ± 34.9^a	63.9 ± 43.5^a
Ca	89.3 ± 20.1	54.2–119.8	165.0 ± 21.1^a	227.2 ± 67.2^b
Mg	13.9 ± 2.4	9.2–19.3	109.9 ± 27.7^a	106.2 ± 28.5^a
S	38.5 ± 8.9	15.3–50.4	216.8 ± 62.5^b	150.3 ± 32.3^a
Na	26.0 ± 5.3	10.8–34.7	130.1 ± 40.7^a	126.9 ± 38.7^a

* The data represent the mean content of nutrients in the fish waste water during the whole fish production period (23.1.2015–08.01.2016), including ± standard deviations and minimum (min.) and maximum (max.) values.
** The nutrient contents in fresh and fish waste water based nutrient solutions are given as mean values calculated for eight consecutive weeks from 02.07.2015 until 27.08.2015 ± standard deviation (n = 8). The detected concentrations were compared using *t*-tests. Significant differences are indicated by small letters ($p < 0.05$).
*** blb = below limit of detection.

NH_4-N concentrations varied between 0.05 mg L^{-1} and 64.1 mg L^{-1} (mean 24.2 mg L^{-1}) and from unverifiable up to 42.7 mg L^{-1} (mean 14.6 mg L^{-1}) for NO_3-N. The concentrations of P, K, Ca, Mg, S and Na in the fish waste water fluctuated between 0.06 and 15.8 mg L^{-1}, 3.2 and 69.1 mg L^{-1}, 54.2 and 119.8 mg L^{-1}, 9.2 and 19.3 mg L^{-1}, 15.3 and 50.4 mg L^{-1}, and 10.8 and 34.7 mg L^{-1}, respectively.

In a period of 8 weeks (02.07.2015 to 27.08.2015), the mean concentration of NH_4-N, K, Mg, and Na did not differ significantly in terms of the fresh water and fish waste water based nutrient solution (Table 3). However, differences in nutrient concentrations were observed regarding NO_3-N, P, Ca and S. NO_3-N, P and Ca were significantly lower (by 45.7 mg L^{-1}, 137.7 mg L^{-1} and 62.2 mg L^{-1}, respectively) owing to the nutrient solution mixed with fresh water. However, the S content was 30.7% higher in the fresh water based nutrient solution.

3.4. Total fresh water use and fertilizer use and their efficiencies

3.4.1. Fresh water consumption and total fresh water use efficiency

From 23.01.2015 (initial fish stocking) until the last day of tomato harvest (27.10.2015) the total fresh water consumption of the RAS amounted to be 160.4 m^3. The aquaponic treatment, with a total of 48 plants, consumed 13.6 m^3, i.e. 8.5% of the available fish waste water, from the day of planting (05.02.2015) until 27.10.2015. However, 14.2 m^3 fresh water were consumed by the hydroponic treatment during the plant growth period.

To investigate the FWUE, a mean yield of 13.05 kg $plant^{-1}$ in the aquaponic treatment was calculated. This resulted in a total fruit yield of 626.5 kg (Table 4), while the RAS achieved a total fish yield of only 248.84 kg. Considering these yields and the water consumption, it can be derived that in the present study 1.55 kg tilapia and 46.1 kg tomato fruit were produced with one m^3 fresh

Table 4
Total yield, total fertilizer addition, and fertilizer use efficiency (FUE) caused by hydroponics and aquaponics.

	hydroponics	aquaponics
Total yield per treatment (kg)	677.3	626.5
Mineral fertilizer addition (kg)	15.5 (100%)*	11.6 (74.8%)*
FUE (kg kg^{-1})**	43.7	54.0

* The percentages in the brackets represent the reduced fertilizer addition in aquaponics compared to hydroponics (100%).
** The FUE is calculated in kg produced tomatoes per kg mineral fertilizer addition.

water applied to the RAS. However, the FWUE reached a value of 47.7 kg m^{-3} caused by the simple hydroponic system, when a total fruit yield of 677.3 kg and a fresh water consumption of 14.2 m^3 were considered.

3.4.2. Fertilizer use and fertilizer use efficiency

The addition of total fertilizer into the aquaponic system was reduced by 25.2% compared to that delivered to plants grown in a simple hydroponic system (Table 4). Based on the total yields and the total fertilizer uses as shown in Table 4, it was calculated that the FUE was improved by 23.6% in favour of the aquaponic system. This means that 10.3 kg more tomatoes can be produced with the application of one kilogram fertilizer into this system compared to a simple hydroponic system.

4. Discussion

4.1. Plant yield and plant growth

The goal to reach comparable yields with the innovative DRAPS as produced in the conventional way was achieved successfully. A total yield of 29.2 kg m^2 was gained using optimised fish waste water (Fig. 2), and thus the new system can compete with modern hydroponic systems (Dannehl et al., 2014a, 2013). Kloas et al. (2015) achieved a total yield of 20.5 kg m^{-2} with the first prototype of DRAPS, where the same time duration of harvest period was considered. That means that the yield was increased by 1.4-fold caused by optimising the DRAPS, especially by the continuous measurement of nutrients and optimisation of the fish waste water for plant requirements (further discussed below) as shown in the present study. Roosta and Hamidpour (2011) demonstrated that in SRAPS equal tomato yields as in conventional hydroponics can be produced when different macro- and micro-nutrients were applied by foliar application. However, the drawback of the mentioned study is that the observation period was only 22 days and is therefore, not meaningful. Wortman (2015) found that the relative vegetative growth rates of basil, kale, tomato and pepper in simulated aquaponics (low EC + high pH) did not differ from plants grown in conventional hydroponics (high EC + low pH). But the marketable yields of all species were significantly reduced in aquaponics. He recommended a fertilizer supplementation to overcome these yield gaps. In the present study, it was demonstrated that with DRAPS comparable tomato yields as in conventional hydroponic can be produced. In addition, the rate of marketable fruits were slightly reduced in aquaponics (−0.5%) when compared with hydroponics (−0.9%) due to the fact that in hydroponics significantly more fruit were affected by BER (0.9%). The reduced amount of BER fruit in aquaponics (0.5%) might be caused by a higher Ca content in the fish waste water based nutrient solution (Table 3) (Millikan et al., 1971).

Although a significant reduction in LA (−15.4%) of plants grown in aquaponics was determined, the number of leaves and the yield were not clearly reduced simultaneously (Table 2). As such, the photosynthesis of plants is a function of the photosynthetic activity (source activity) and photosynthetic area (source size) (Engels et al., 2012). The lower assimilate supply by a reduced source strength in consequence of a reduced LA did not affect the yield obviously. One reason for this result might be the fact that the Chl NDI in leaves influenced by aquaponics was significantly increased (+17.9%). The Chl NDI is an indicator for the chlorophyll content in leaves (Richardson et al., 2002), where the chlorophyll content is directly linked to the source activity and therefore, to the photosynthesis and consequently to the assimilate supply. Based on the higher Chl NDI value, it might be possible that the photosynthesis of plants grown under aquaponic conditions was more efficient followed by an accumulation of more primary metabolites in fruit, whereby the fruit yield was not influenced negatively.

4.2. Fruit quality

Plants grown in aquaponics developed fruits with a significantly lower DM content (5.12%) compared to those influenced by hydroponics (5.37%). However, in both treatments the DM content was in the range as reported for tomatoes (Frusciante et al., 2007; Herrmann, 1979). In the present study, the nitrate nitrogen content in the nutrient solution was significantly reduced in hydroponics (Table 3) during the ripening period. Beínard et al. (2009) reported that low nitrogen supply result in an increased DM content and consequently improved fruit quality in terms of SSC. Both, SSC and SAR were significantly increased in hydroponic production (+6.9%, +5.0%, respectively) (Fig. 3). It has been reported that the overall flavour of tomato fruit is among other things depending on SSC and SAR (Baldwin et al., 1998; Stevens et al., 1979). Baldwin et al. (1998) found that SAR and SSC are positively correlated with an overall acceptability of tomato fruit among consumers. It was not proven, but it might be possible that the fruit flavour of tomatoes produced in hydroponics differed positively to tomatoes ripened under the influence of aquaponics. Due to the fact that the taste influences the purchasing behaviour of consumers (Pollard et al., 2002), the fruit produced by aquaponics are only competitive when they have a good taste. Therefore, a sensory analysis should be carried out in further experiments.

It is generally accepted that the diet and nutrition are central factors for a good health and that they play a key role in the prevention of chronic non-communicable diseases (NCDs) (WHO, 1990). NCDs are responsible for 63% of the global deaths (WHO, 2013). In this context, it has been reported that the consumption of tomatoes is associated with decreasing cardiovascular diseases and forms of cancer (Agarwal and Rao, 2000; Giovannucci, 1999). The main carotenoids of tomatoes are lycopene and ß-carotene, which are mostly responsible for these beneficial facts. They are antioxidants and react with free radicals or singlet oxygen (Di Mascio et al., 1989). In the human diet the major source of lycopene are tomatoes and tomato products (Stahl and Sies, 1996). Compared to results found for carotenoids in tomatoes by Frusciante et al. (2007), the lycopene and ß-carotene contents in fruit represented in the current study can be classified as high. It was reported that the lycopene content in tomatoes increased with increasing P or S supply, whereas this metabolite was negatively correlated to higher N and Ca supplies (Dumas et al., 2003; Montagu and Goh, 1990; Zelená et al., 2009). The same negative correlation applies between ß-carotene and different Ca applications (Dumas et al., 2003). In the present study, however, the fruit lycopene and ß-carotene contents did not differ significantly, although the content of S was significantly higher in hydroponics and that of NO_3-N, P and Ca content in aquaponics (Table 3).

during the ripening period. In terms of aquaponics, less information can be found about quality parameters regarding primary and secondary metabolites in plants. More research on quality parameters is necessary to provide not only sustainability facts

about aquaponics, but also information about health-promoting plant compounds accumulated more or less in aquaponic products, which is necessary because quality aspects become more and more important for consumers (Pollard et al., 2002).

4.3. Water and fertilizer use and its efficiency

4.3.1. Water use and fresh water use efficiency

The plant unit consumed only 8.5% of the available fish waste water (see 3.4.1). Extrapolated to the whole canopy, the plants in the greenhouse (144 plants) would consume 40.8 m^3, i.e. 25.3% of the fish waste water (from 161 m^3) generated by aquaculture and a daily exchange rate of 6.3%. This result suggests that the used research plant does not have the optimal RAS to greenhouse ratio. As shown above, approximately 161 m^3 fish waste water were available. Based on the results that 144 plants would consume 40.8 m^3 fish waste water, it can be calculated that 568 plants could be produced under consideration of 161 m^3 fish waste water, which is generated during fish production at a total productive volume of 7.2 m^3. With these numbers of plants and taking into account a plant density of 2.3 plants per square metre used in the present study, the optimal ratio between fish and plant unit would be a total productive volume of 7.2 m^3 and a net-acreage in the greenhouse of 247 m^2. Considering these data, a fish tank containing a volume of one cubic metre can be used to irrigate plants growing on a greenhouse net-acreage of 34.3 m^2. These calculations are strictly related to the combined production of tilapia and tomatoes as shown in the present study.

However, as already mentioned the set-up of the RAS for efficient tilapia production was hampered due to the changing environmental testing conditions during the experimental period. Therefore, productivity and stocking was much lower than described by Kloas et al. (2015). In the present study it was demonstrated that per cubic metre fresh water use only 1.55 kg fish but 46.1 kg tomato fruits were produced using the recently constructed DRAPS, whereas a not much higher yield was obtained (47.7 kg tomatoes) using the hydroponic system. Kloas et al. (2015) calculated that they could produce 5 kg tilapia and 25 kg tomatoes with the application of 1 m^3 fresh water to the RAS. The reason for the lower fish production per m^3 fresh water in the present study can be explained by two facts. First the much lower fish stocking density (20.7 kg m^{-3}) compared to that applied by Kloas et al. (2015). Secondly Kloas et al. (2015) used a technically higher advanced system to reuse the evapotranspirated water from plants and water surface via condensation in the RAS. The higher tomato yield production in the present study can be explained by a better control and fertilizer strategy in the present study compared to the study of Kloas et al. (2015). In the present study the stock nutrient solution for the plants were adjusted regularly and very specific to the nutrient content of the used fish waste water. Furthermore, Kloas et al. (2015) stopped the continuous addition of micro nutrients in between the harvest period. All this resulted in lower K and Fe contents in the nutrient solution for the plant unit than recommended for tomatoes in the mentioned study. These deficiencies might be a reason for the reduced yields. In this context it was reported that K has a positive effect on tomato fruit yield (Almeselmani et al., 2009). Roosta and Hamidpour (2011) found a positive effect of K and Fe foliar application on tomato fruit yield.

Finally, the research plant in the present study was built as a light version, i.e. without active cooling unit in the greenhouse. The installation of finned tube heat exchanger as an active cooling system in the aquaponic plant can lead to further water savings because it was found that 143 L m^{-2} condensation water can be collected during an annual tomato production (Dannehl et al., 2014c). A further advantage of this cooling system would be that the ventilation can be closed for a longer time resulting in higher CO_2 levels and an associated faster vegetative crop growth, higher yields and an increased accumulation of primary and secondary plant metabolites in fruit (Dannehl et al., 2014a, 2013). Furthermore, the water uptake of the plants can be reduced which results in a better water use efficiency (Dannehl et al., 2014b).

4.3.2. Fertilizer use and fertilizer use efficiency

The total fertilizer use in aquaponics was reduced by 25.2% compared to the control (Table 4). This was not as high as expected. The nutrient load, especially that of the nitrogen content in the fish waste water was unexpectedly low compared to the results by Kloas et al. (2015) using an established near-to-optimum productivity for tilapia. While Kloas et al. (2015) calculated a mean NO_3-N content of 127.7 mg L^{-1}, the used fish water in the present study contained only an average of 14.6 mg L^{-1}. The content of K, Ca, Mg and S was also reduced by 50.7%, 58.1%, 57.0% and 30.3%, respectively, compared to the results obtained in the study of Kloas et al. (2015). The lower nutrients in the present study were caused by the lower fish stocking density compared to that applied in the mentioned study. On the other hand, Kloas et al. (2015) achieved lower NH_4-N concentrations (5.79 mg L^{-1}) as found in the current study (24.2 mg L^{-1}). It might be possible that this circumstance was triggered by different measuring points. While Kloas et al. (2015) measured NH_4-N directly in the RAS before passing the fish water to the hydroponics reservoir tank, the present results were obtained by measurements in the storage tank after the fish waste water passed the 3-cp. Low ventilation of the 3-cp could be one reason for the higher NH_4-N content. Based on these results, it is assumed that an optimisation of the fish production in the RAS system and aeration of the 3-cp would deliver more nutrients for the plant production, which offers the possibility to increase markedly fertilizer savings in the range as described by Kloas et al. (2015).

The unique separation of the fish and plant cycle is one key advantage of DRAPS, due to the possibility to optimise the conditions (pH, nutrients) for fish and plants independently from each other. As shown in the present study, it is possible to realise also a good plant growth and fruit yields as in a simple hydroponic system with lower nutrient concentrations generated by the fish of the RAS, but only if sufficient nutrients are added to the nutrient solution for the plant unit. To ensure that nutrients are added in an optimal concentration for the plant growth, continuously measurements of the nutrients in the fish waste water and regularly adjustments of the fertilizers in the fish waste water based nutrient solution are indispensable. In this context, the best solution for DRAPS would be the installation of ion sensitive sensors with a direct feedback control as reported by Kläring (2001).

In the present study, it has been successfully demonstrated that the total yield produced in aquaponics is comparable to that in hydroponics and the fertilizer use efficiency was increased by approximately 23.6%. Applying 1 kg mineral fertilizer led to a fruit production of 54.0 kg in aquaponics, whereas only 43.7 kg tomatoes were produced in hydroponics (Table 4). However, if the fish productivity would have been in a similar range as demonstrated by Kloas et al. (2015), the fertilizer savings might have been much higher. This is the aim of ongoing studies.

5. Conclusion

It was shown that a double recirculating aquaponic system (DRAPS) with two independent cycles provides the opportunity to produce equal tomato yields compared to those obtained by conventionally used hydroponic systems. Moreover, it was demonstrated that even with a suboptimal fish production a good plant growth and fruit yield can be guaranteed using DRAPS. Never-

theless, to ensure that the added nutrients are in an optimal concentration for the plant growth, continuous measurements of the nutrients in the fish waste water and regular adjustments of the fertilizers in the nutrient solution are indispensable.

DRAPS allows an intensive as well as a more sustainable food production. As such, it was found that the joint use of 1 m^3 fresh water resulted in 46.1 kg tomato production plus 1.5 kg tilapia, whereas only one food product, namely 47.7 kg tomatoes, was produced in hydroponics with the same volume of water. The fertilizer use efficiency was also improved by 23.6%. The results show that DRAPS contributes to lower the operating costs of plant production and to relief the environment, which is mainly based on the reuse of fish waste water and associated reduced quantity of nutrient emission. Additionally, the latter might be also interesting for fish farmer because in some countries the disposal is associated with high costs.

Moreover, it was demonstrated that even the sustainable produced food with DRAPS has a high quality, similar to conventional produced products. The contents of lycopene and ß-carotene in fruit matured under present aquaponic conditions were comparable to those in the hydroponics ones.

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