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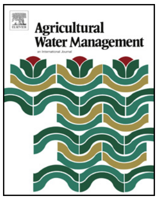

Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics

Johanna Suhl[a,b,*], Dennis Dannehl[b], Werner Kloas[c,d], Daniela Baganz[a], Sebastian Jobs[e], Günther Scheibe[e], Uwe Schmidt[b]

[a] *Department of Biology and Ecology of Fishes, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 301, 12587 Berlin, Germany*
[b] *Faculty of Life Sciences, Albrecht Daniel Thaer – Institute of Agricultural and Horticultural Sciences, Division Biosystems Engineering, Humboldt-Universität zu Berlin, Albrecht-Thaer-Weg 3, 14195 Berlin, Germany*
[c] *Department of Ecophysiology and Aquaculture, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany*
[d] *Faculty of Life Sciences, Institute of Biology, Department of Endocrinology, Humboldt Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany*
[e] *PAL-Anlagenbau GmbH Abtshagen, Amtsweg 6, 18510 Wittenhagen/Abtshagen, Germany*

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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.

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-

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Abbreviations: %, percentage; $^\circ$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.

[*] Corresponding author at: Department of Biology and Ecology of Fishes, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 301, 12587 Berlin, Germany. Tel.: +49 30209346414; fax: +49 30209346415.
E-mail address: suhl@igb-berlin.de (J. Suhl).

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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 ($\text{pH} > 7$), 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