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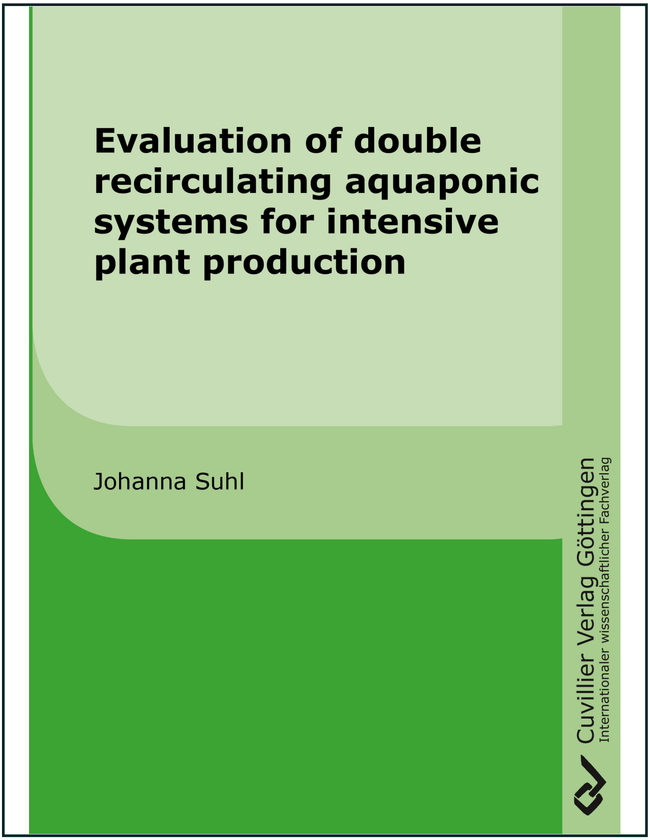
Evaluation of double recirculating aquaponic systems for intensive plant production



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1 General introduction

1.1 Scientific background

Agriculture is sitting on the fence. On the one hand there is a growing world population which needs to be fed, and on the other hand agriculture is affected by climate change but also water and energy scarcity. The world´s population is predicted to rise to nearly nine to ten billion by 2050 (worldometers.info). Therefore the overall food production has to increase by 70% calculated from 2005/07 to 2050 (FAO, 2009). At the same time agriculture is responsible for 24% of the global greenhouse gas emissions, mainly CH_4 and N_2O (Edenhofer et al., 2014) and withdrawal of nearly 70% of the global fresh water resources (FAO, 2016a). Intensive food production systems like vegetable production in greenhouses and aquaculture are highly productive on the one hand, but also have a significant negative impact on the environment. However, the current significant research efforts and developments have been made to make these systems more environmentally friendly. Sustainable food production systems with low resource requirements, and simultaneously high biomass output, become more and more important for the future and is referred to as sustainable intensification (Godfray et al., 2010).

One suitable option for this is the relatively new technology of double recirculating aquaponic system (DRAPS) – a high-tech system for intensive, but more sustainable food production. Generally, aquaponics uses the synergetic effects of the combined production of fish and plants. Conventional single recirculating aquaponic systems (SRAPS) are also referred to as one-loop systems are low-tech aquaponics. It is an old approach to use nutrients and water twice by producing two cash crops. As such, the nutrient-rich fish water is used to irrigate and feed the hydroponically grown plants, while the fish water itself is simultaneously cleaned from fish toxic ammonium. The functionality of SRAPS is based on the interaction of three different biological systems, fish, bacteria and plants. But the associated challenge, the different environmental requirements of the three species, prevented aquaponics from its implementation as a key player for large-scale production units, so far.

Recently, aquaponics was rethought and a new concept was developed to solve this challenge. This new, high-tech aquaponic system is based on two separate and independent working recirculating systems. As such, a recirculating aquaculture system (RAS) and a recirculating (closed) hydroponic system are connected unidirectionally. Independent working means that both units can generally operate completely without each other. Certainly, the fish water is still used to irrigate and feed the plants, but the water from the plants is not delivered back to the fish directly. This provides the opportunity for optimisation of fish water and adjustment specifically to the requirements of the respective plants. Mineral fertiliser and acid is added to adjust the nutrient concentration or the pH value. This, in turn, means that the fish, as well as the plants, can be produced under optimal and intensive conditions. These systems are referred to as double recirculating aquaponic system (DRAPS) or decoupled aquaponics. The concept of DRAPS is relatively new and the current state of research is given in section 2.3.2.

1.2 Delimitation, aims, and objectives of the present study

1.2.1 Delimitation to already published theses

Recently two doctoral theses dealing more or less with DRAPS were published. The titles are "Opportunities and Challenges of Multi-Loop Aquaponic Systems" written by Simon Goddek (2017) and "Overcoming major bottlenecks in aquaponics – A practical approach" written by Hendrik Monsees (2018). A third thesis studied DRAPS only at the edge and was written by Delaide (2017). However, his main subject was on single recirculating aquaponics, and in terms of DRAPS, he worked closely together with Goddek (2017). Therefore Delaides thesis will not be considered at this place. The already published theses might raise the question if a further thesis can contribute increasing the knowledge in terms of DRAPS. In the following is demonstrated why the present thesis has its justification.

The major topics of the different theses differed or even came to different results which are discussed in the present thesis. Goddek (2017) worked in his thesis with smaller experimental setups and with technical approaches, where he modelled aquaponic systems with different technical components. Briefly, his experimental setups were conducted in separated hydroponics systems using the "idea" of DRAPS. He used fish water to irrigate the plants but he did not work in a whole operating DRAPS. In another experimental setup, he investigated the remobilization of nutrients from sludge under anaerobic conditions. Additionally, Goddek (2017) included two technical chapters where he designed and modelled a multi-loop aquaponic system including a further anaerobic nutrient remobilization component or desalination technology.

In contrast, Monsees (2018) worked partly in a whole operating double recirculating aquaponic system (in the prototype of DRAPS developed and build by Rennert et al. (2011) and Kloas et al. (2015), slightly modified). His thesis is divided into three main sections. Initially, he identified which nitrate concentration Nile tilapia can be produced in RAS without negatively affecting health and growth. In his 2nd experiment, he compared DRAPS and SRAPS under real conditions with the DRAPS prototype in terms of fish production and plant growth. The last main chapter deals also with sludge treatment for nutrient remobilisation like Goddek (2017). The results of both are further discussed in subsection 2.3.2.

Besides the valuable studies of both, there is a missing proof of concept on an intensive production basis. Even if Monsees (2018) worked already with a whole DRAPS, comparing DRAPS with low-tech single recirculating aquaponic systems (SRAPS). But for the implementation as large-scale or intensive food production system, the comparison to conventional hydroponically single production is absolutely necessary. This was compared already by Goddek (2017). However, he conducted relatively small scale experiments without using a whole operating DRAPS. Additionally, he did not evaluate a whole DRAPS during a whole year production cycle. Therefore, one major subject of the present thesis was to evaluate an operating DRAPS as a whole system during a whole year production cycle in comparison to conventional hydroponics. Besides this, some further subjects, which were not considered by the mentioned theses, were examined. The more detailed aims and objectives are given in the following.

1.2.2 Aims and objectives of the present study

As mentioned above, due to the missing proof of concept on an intensive production basis one major subject of the present thesis was to evaluate the DRAPS as a whole. Unfortunately, it was not possible to build three or more identical DRAPS. Therefore, the experimental setup occurred primarily in the hydroponic unit. That means that the used DRAPS had only one RAS but different hydroponic treatments. Nevertheless, the specified view to the hydroponic was absolutely necessary because in DRAPS the hydroponic unit is directly dependent on the fish rearing system and the adjustment unit. DRAPS has especially to compete with intensive single vegetable production in soilless culture. Thus, the plant performance in DRAPS was compared to plant performance by conventional hydroponics. As such, not only the quantity output of the system but also qualitative aspects of the produced vegetables were investigated. The latter was of great importance because very little is known about the effect of DRAPS, or aquaponics in general, on fruit quality parameters. The connection point between both cycles, the recirculating aquaculture system (RAS) and the hydroponic unit, was another focus of the present thesis. Therefore, the nutrient and oxygen concentrations were measured to investigate whether the components between the RAS and the hydroponic unit do have an impact. In this context, some problems were identified and the DRAPS modified during the study to address these issues. A first evaluation of the modifications was also done and is part of the present thesis.

Nile tilapia (*Oreochromis niloticus*) is one of the most utilised fish for aquaculture and is relatively robust. Probably due to this fact the few studies to DRAPS were just working with tilapia. As such, the present thesis was also used to examine if the concept of DRAPS is also useful to rear fish species other than Nile tilapia (under conventional practical conditions). Therefore, in the 2nd experiment (Table 1) or production cycle, the more famous aquaculture fish in Germany, the African catfish (*Clarias gariepinus*) were produced.

Due to the knowledge that fish waste water contains more soluble solids and microorganism than tap water, additionally, the oxygen concentrations of the nutrient solutions used in conventional hydroponics and in DRAPS were monitored. The aim was to evaluate if there were differences and if the differences can be traced back to the use of process water.

The results, found by Delaide et al. (2016) or Goddek (2017), did not confirm the results of the first experiment (Table 1) of the present thesis. Therefore, a further experiment was conducted (experiment 3, Table 1). To investigate the different statements; a small scaled experiment was conducted where only a hydroponic unit and not a whole DRAPS were used.

To evaluate how sustainable DRAPS are, the fresh water and fertiliser saving potential were investigated in comparison to that used by conventional hydroponics. Furthermore, it was calculated how much emissions can be saved by replacing nitrogen fertiliser with fish waste water.

In summary, the overall aim of the present study was a proof of concept of DRAPS as an intensive food production system with the main focus on the hydroponic unit. Based on this, the following specific objectives were formulated to meet the overall aim:

i) Determination of tomato and lettuce growth in terms of quantity and quality aspects under conditions of double recirculating systems in comparison to conventional hydroponic vegetable production.
ii) Examination of nutrient solution quality in terms of oxygen.
iii) Investigation of the nutrient concentration and the effect of the connection point between fish and plant unit.
iv) Evaluation of the fertiliser-saving potential and the environmental relief using DRAPS compared to conventional hydroponics.
v) Testing if DRAPS can be operated successfully with African catfish.
vi) Evaluation of the modification of the used DRAPS.*
vii) Direct comparison of nutrient solutions (based on fish waste water (DRAPS) and fresh water (conventional hydroponics)) to investigate the influence of the natural microorganism community on plant growth.

*Due to first research results a modification of the original constructed INAPRO research DRAPS were carried out.

1.3 Set-up of the thesis and short methodical overview

1.3.1 Overview

The scientific background of the present thesis is described in the 1st chapter, the general introduction and gives a brief introduction to the topic. A further part of the general introduction is the description of the aims and objectives of the present thesis (subsection 1.2.2). Due to recently published theses regarding double recirculating aquaponic systems, subsection 1.2.1 briefly describes what the present thesis differentiates from the other both.

The current state of knowledge is outlined in the second chapter. This chapter starts with a description of the impact of hydroponics on the environment (2.1) and a brief overview of aquaculture systems, especially recirculating aquaculture systems (2.2). It is followed by the subsection aquaponics which is again divided into two subsections. While the 1st subsection (2.3.1) deals with conventional low-tech, single recirculating aquaponic systems (SRAPS) and its bottlenecks, the second subsection (2.3.2) gives an overview about the current status of high-tech, double recirculating aquaponic systems (DRAPS).

The present thesis is a cumulative work. To meet the defined objectives three main experiments were conducted which are presented here in six different research papers or proceedings, respectively, separated in the chapters 3 to 8. For better understanding Table 1 gives a schematic overview of the chapters, the related experiments and the respective met objectives were already described in 1.2.2.

Table 1: Schematic overview of the chapters of the present thesis, the related experiments and the respective met objectives (1.2.2).

<table>
<tr><td colspan="3">Chapter 1
General introduction</td></tr>
<tr><td colspan="3">Chapter 2
State of knowledge</td></tr>
<tr><td>Experiment 1
2015
INAPRO[1] research DRAPS
Nile tilapia + tomato</td><td>Experiment 2
2016 + 2017
INAPRO research DRAPS
African catfish + tomato</td><td>Experiment 3
2016
Separated experiment; only with hydroponic unit[2]</td></tr>
<tr><td>Chapter 3
Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics
(objectives i, iii)

Chapter 4
The potential of double recirculating aquaponic systems for intensive tomato production
(objectives i)

Chapter 5
Oxygen consumption in recirculating nutrient film technique in aquaponics
(objectives ii)</td><td>Chapter 6
(2016)
An innovative suction filter device reduces nitrogen loss in double recirculating aquaponic systems
(objectives i, iii, iv, v, vi)

Chapter 7
(2016 + 2017)
Prospects and challenges of double recirculating aquaponic systems (DRAPS) for intensive plant production
(objectives v, vi)</td><td>Chapter 8
Lettuce (Lactuca sativa, variety Salanova) production in decoupled aquaponic systems: Same yield and similar quality as in conventional hydroponic systems but drastically reduced greenhouse gas emissions by saving inorganic fertiliser
(objectives i, iii, iv, vii)</td></tr>
<tr><td colspan="3">Chapter 9
General discussion</td></tr>
<tr><td colspan="3">Chapter 10
General conclusion and recommendations</td></tr>
</table>

[1]EU project: Innovative aquaponics for professional application.

[2]Hydroponic unit at Humboldt-Universität zu Berlin, Albrecht Daniel Thaer – Institute of Agricultural and Horticultural Sciences and fish waste water (Nile tilapia) from Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin

DRAPS = double recirculating aquaponic system.

For the experiments 1 and 2 a new designed DRAPS – the INAPRO[1] research DRAPS – were used (experiment 1 and 2). For the INAPRO aquaponic system some parts of the prototype DRAPS developed by Kloas et al. (2015) were enhanced. A detailed system design and the main changing of the INAPRO research DRAPS are exactly described in chapter 3.

1.3.2 Experiment 1

In the 1st experiment, Nile tilapia and tomatoes were grown and it was mainly focused on the development and productivity of the tomato plants. This experiment was the content of the chapters 3, 4, and 5. Chapter 3 was mainly focused on a direct comparison of DRAPS and conventional hydroponics at the same electrical conductivity (EC) level of the nutrient solution for the plants (EC 1.8). Chapter 4 focuses on the evaluation of an increased EC level in aquaponics (EC 3.0).

Beside the plant growth, experiment 1 was dealing with the evaluation of the fruit quality in terms of secondary metabolites. Another focus of this experiment was on the evaluation of the nutrient concentration in the fish waste water. For completion, the saving potential of fresh water and fertiliser were calculated and compared to conventional hydroponics.

The 4th chapter includes more detailed evaluation of plant growth parameters but also evaluates the fruit quality in terms of the nutrient concentration.

Parallel to the mentioned investigation, the 1st experiment was also used to determine the oxygen concentration in the cultivation trenches and is also part of chapter 5. For evaluation, the oxygen consumption was calculated and it was investigated whether the nutrient solution itself (without plants) affected the oxygen consumption.

The 1st experiment was furthermore used to calculate the total biomass output and to calculate the area production ratio between aquaculture and hydroponic unit.

1.3.3 Experiment 2

In the 2nd experiment, Nile tilapia was replaced by African catfish and was the basis of the chapters 6 and 7. African catfish were used for the first time as combination partner in DRAPS. Therefore, the second experiment was done to evaluate if African catfish are usable for DRAPS. Therefore the plant

[1]EU project: Innovative aquaponics for professional application.

production in terms of fruit quantity was investigated. However, the focus in experiment 2 was less on plant performance than on the modification of the original INAPRO research DRAPS (in the following referred to as `original DRAPS´). The modification is described in both chapters and was absolutely necessary due to nitrogen loss in the original DRAPS. This in turn resulted in a fertiliser reduction far below its potential. Due to the high nitrogen fertiliser saving potential, the evaluation of the second experiment was further focused on the potential to reduce greenhouse gas emissions. As in the 1st experiment, the biomass output and the area production ratio between aquaculture and hydroponic was calculated.

After modification the nutrient concentration in the fish water (samples in the RAS) were investigated on 3 and 15 consecutive days, respectively. The second measurement (15 days) was done only in 2017 and is part of the chapter 7.

1.3.4 Experiment 3

The 3rd experiment (chapter 8) was detached from the INAPRO research DRAPS, and water from a running Nile tilapia RAS was used to grow lettuce (Table 2). This investigation was done to scrutinise the 1st and the 7th objective (1.2.2) of the present thesis. Interestingly, while the 1st experiment was carried out, a study was published where contrasting results were found (Delaide et al., 2016). The authors found significant and much higher yields (+39%) in "DRAPS" (they did not use a whole DRAPS system) compared to conventional hydroponics. Therefore, the 3rd experiment was conducted to investigate the possibly better growth of lettuce in DRAPS than in conventional hydroponics.[2] Additionally, the effect of the natural microorganism community in fish water on plant growth was investigated.

For experiment 3 exact nutrient solutions were prepared by hand. Therefore the results were also used to calculate the fertiliser saving potential. Additionally, the environmental relief due to reduced fertiliser supply was calculated.

1.3.5 General discussion and conclusion

In chapter 9 the results of the different experiments are discussed together. Additionally, some contributing results, which could not be pre-

[2]Addendum: Interestingly the results found by Delaide (2016) were recently confirmed by Goddek (2018), even if the yield increment in "DRAPS" was clearly less strong (see chapter 9.1.).

sented in the chapters before, were added. A few selected topics, which were estimated as particularly important, are discussed in chapter 9. This includes the evaluation of plant performance, the nutrient management, the optimal fish to plant ratio, and the environmental relief.

The thesis closes with a general conclusion and recommendations (chapter 10). The chapter starts with a brief reflection on the specific objectives listed in subsection 1.2.2. Afterward a summary of advantages and disadvantages is given using the SWOT analysis format. . To give a comprehensive overview not only the results of the present experiments, but also the experience gained during the four project years of INAPRO will be considered in this part. It is followed by a summary and evaluation of the improvements of the used DRAPS. Finally, the thesis will close with an outlook and recommendations for further research.