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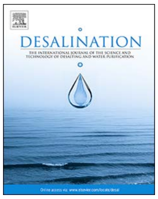

The necessity of desalination technology for designing and sizing multi-loop aquaponics systems

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ABSTRACT

Providing both fish and plants with optimal environmental conditions is a classical problem in the field of aquaponics. Several studies have tackled this problem by decoupling fish and plant systems. However, in order to achieve both high nutrient levels for the plants and low nutrient and particulate loading in the fish tanks, suspended matter in the aquaculture component needs to be discharged and fertilizer needs to be added to the plants continuously. The present study aims to explore to what degree desalination technology could potentially be used to provide the necessary balance between the two different components based on a theoretical modelling approach using contemporary source material. We suggest how specific desalination engineering approaches can improve the nutrient balances in multi-loop aquaponics systems in order to attain optimal growth conditions for both fish and plants.

1. Introduction

Climate change requires innovative agricultural approaches to food security, particularly in countries facing water scarcity and chronic drought. In this context, aquaponics has been identified as a farming approach that, through nutrient and waste recycling, can aid in addressing sustainable development goals, particularly for arid regions.

Traditional designs for one-loop aquaponics systems comprise both aquaculture and hydroponics units between which water recirculates. In such traditional systems, it is necessary to make trade-offs conditions of both subsystems in terms of pH, temperature, and nutrient concentrations [1]. Decoupled double-loop aquaponics systems separate the aquaculture and aquaponics units from one another, with inherent advantages for both plants and fish [2,3]. A decoupled three-loop system as described by Goddek et al. [4] consists of a recirculating aquaculture system (RAS) loop, a hydroponic (HP) loop, and a mineralization loop. The benefits of a decoupled approach is that environmental conditions of each loop can be adapted to the species-dependent requirements that, by reducing trade-offs, can lead to enhanced growth performance [5–7].

Several studies have previously suggested a rule of thumb for general nutrient demands of plants within one-loop aquaponics systems, such that leafy plants (e.g. lettuce, spinach, basil) require between 20 and 50 g fish feed per m^2 cultivation area, and fruity plants (e.g. tomatoes, bell pepper, eggplants) require between 50 and 80 g fish feed per m^2 [8–11]. However, none of these studies has examined scale with respect to the total nutrient demands of the plants. The system dynamics model presented by Goddek et al. [12] showed that decoupled three-loop aquaponics systems are evapotranspiration-dependent and that a mineralization-loop can improve performance. In a unidirectional flow approach, the macro- and micro-nutrient concentration in the RAS loop is automatically consistently higher than in the hydroponic component (i.e. without additional fertilizer inputs). As shown in Table 1, the converse should be true. Moreover, this cannot be altered by the fact that the mineralization loop supplies the hydroponic component with additional nutrients. In short, decoupled approaches require a significant amount of additional fertilizer or nutrient manipulation in order to meet the optimal growth parameters.

One possible solution to this conundrum would be to increase nutrient concentration in the hydroponic loop, while ensuring RAS water conditions meet specific species requirements. Desalination technologies have the potential to separate dissolved salts and other minerals from water [25,26]. In the context of aquaponics, and as an alternative to additional fertilization with corresponding extra costs, desalination technology could not only provide fresh water to the system, but also ensure desired nutrient concentrations for the food producing sub-systems.

The objective of this study is to demonstrate how implementation of desalination processes could solve specific technical problems within current decoupled aquaponics systems by increasing the nutrient concentration within the hydroponic loop, while ensuring preferable nutrient-poor conditions for the fish. In this computer-aided design study,

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Table 1

Optimal environmental factors for cold and warm water fish species, as well as leafy (lettuce) and fruity (tomato) vegetables. It should be noted that ammonium (NH_4) levels are not taken into account here, even though there is evidence that the presence of NH_4 stimulates NO_3 uptake [13]. Note that preferred hydroponic NH_4 levels are lethal for all fish species [14].

Sub-system	Species/type	pH	Temperature (°C)	Nitrate (NO_3) (ppm)
RAS	*Oreochromis niloticus* (Nile tilapia)	7–9 [15]	27–30 [16]	< 100–200[17]
	Oncorhynchus mykiss (rainbow trout)	6.5–8.5 [18]	15 [19]	< 40 [20,21]
Hydroponics	*Lactuca sativa* (lettuce)	5.5–6.5 [22]	21–25 [22]	> 700 [22]
	Lycopersicon esculentum (tomato)	6.3–6.5 [23]	18–24 [23]	666 [24]

we use experimental parameters for growing both lettuce and tilapia, and historical weather data from Namibia to model the potential implementation of desalination technologies (i.e. as a fourth loop added to the three-loop aquaponics system; Goddek et al. [12]), following a numerical approach.

2. Methodology

2.1. Dynamic systems analysis

The *AnyLogic* model used in this study for system design analysis is based on the model initially proposed by Goddek et al. [12]. AnyLogic is a Java-based multimethod simulation-modelling tool. In this study, AnyLogic PLE Version 8.1 was used. The dynamic systems analysis focused on the evaluation of N-balances within multi-loop aquaponics systems following the feed per square meter rule of thumb. N-balances were evaluated in the presence and absence of desalination technology.

Fig. 1 shows a flow chart of a multi-loop system incorporating a decoupled four-loop aquaponics system consisting of: (1) a RAS loop; (2) a hydroponic loop; (3) a mineralization loop; and (4) a desalination (i.e. nutrient concentration) loop.

The model was initially developed to estimate the desired scale of the hydroponic component for *Lactuca sativa* following a one-loop approach, where details on crop growth parameters can be found in [12]. Based on predicted model outputs, the impact of design parameters on the nitrate (NO_3) mass balances in RAS and HP loop can be evaluated for a decoupled RAS and hydroponic subsystems.

2.2. Input data and parametrization

2.2.1. Recirculating aquaculture system

A relatively small RAS with corresponding HP loop was used in this model-based study to make the model output more comprehensible. The RAS with corresponding parameter values are the same as in the

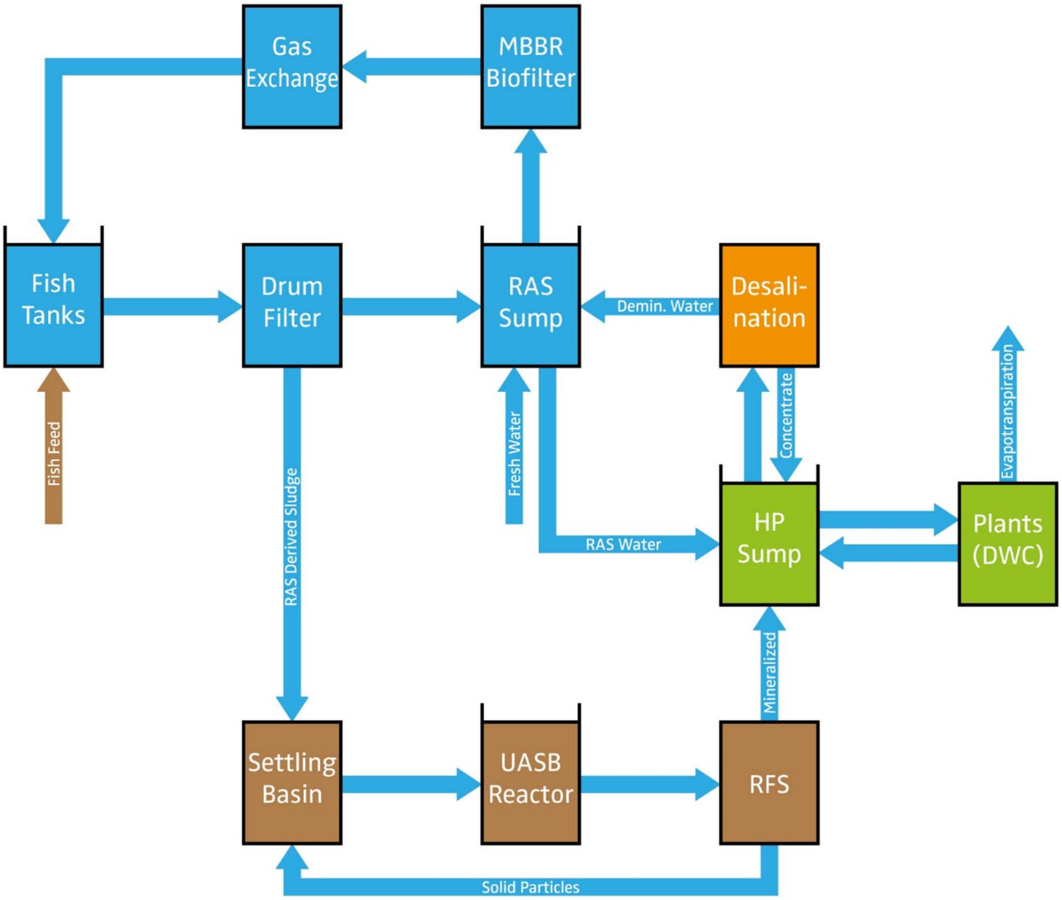

Fig. 1. Water flow scheme of the multi-loop aquaponics system as proposed in this study using *AnyLogic* system modelling software; where the blue boxes represent the RAS system, green boxes the hydroponic system, brown boxes the mineralization loop, and the orange box the desalination plant. Water from the hydroponics sump is being concentrated in the desalination plant resulting in two separated flows: (1) demineralized water to the RAS, and (2) concentrated nutrient solution (i.e. brine) flowing back to the hydroponic loop. (RFS = radial flow settler; UASB = upflow anaerobic sludge blanket reactor; DWC = deep water culture; HP = hydroponic; MBBR = moving bed bio reactor). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)