Biobased Chemistry and Technology

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Modelling innovative aquaponics farming in Kenya

Klaas Hielke Dijkgraaf

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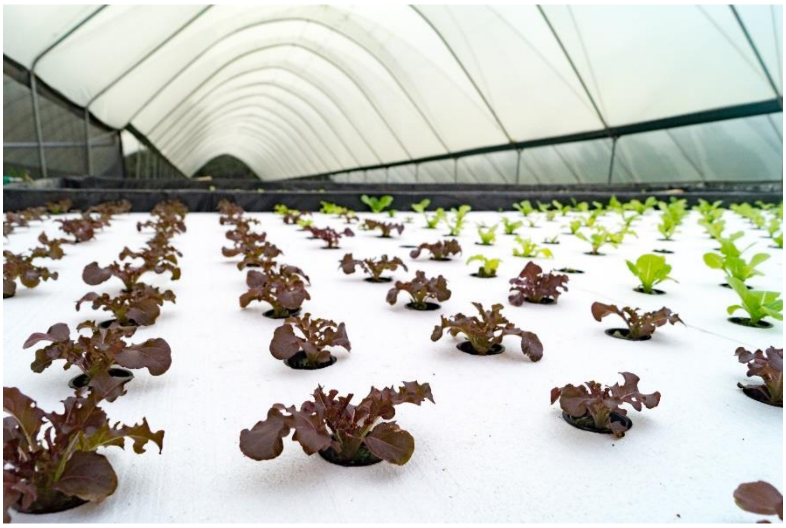

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Modelling innovative aquaponics farming in Kenya

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Abstract

Aquaponics combines hydroponics and aquaculture in order to produce food in an environmentally sustainable way, meaning nutrients, water, and energy are efficiently used. The KeniAP system is an aquaponic system near Nairobi that produces Nile tilapia in a 50 m^3 RAS, and tomato and lettuce in a 1500 m^2 HPS. Fish sludge is captured and converted into biogas, mineralized nutrients, and waste sludge. Biogas and solar energy are converted into electrical energy to power the aquaponic system. Solar thermal energy is collected and used to heat incoming groundwater to the temperature suitable for Nile tilapia. The aim of this research study was to gain insight into the dynamics of the KeniAP system, to facilitate optimization of the system in terms of nutrient, water, and energy use, and to understand the effect of uncertain parameters on the system. A model of nutrient and water streams was created, and the energy balance of the system was determined. Nitrogen and phosphorus were the considered nutrients in the model. Using the model, the system design was optimized and an uncertainty analysis was performed. Efficient use of nutrients and water is achieved by setting system design parameters in a way that no dilution of the nutrient solution occurs. The addition of an anaerobic digester greatly increases the nutrient and water use efficiency of the system. Optimal system sizing is a 50 m^3 RAS and 2627 m^2 HPS. Model outputs are most sensitive to uncertainty in fish feed P content and P mineralization rate of the digester.

Preface

I would like to thank Simon Goddek for his assistance and supervision during this research study. He helped me in understanding aquaponic system design and answered all kinds of questions that came up during this year. Next to that, I would like to thank Karel Keesman for his critical remarks and guidance during this project. After our meetings, it was always clear how to continue, and what aspects needed attention. Furthermore, I would like to thank Joost Goedhart and Jeroen Zwietering for their company during the most part of this year, it was a welcome distraction most of the time. Lastly, I would like to thank the chair group Biobased Chemistry and Technology for making resources available for me to use.

Contents

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List of tables

List of figures

List of abbreviations

Symbol	Definition
FCR	Feed Conversion Ratio
WT	Fish Weight
NFT	Nutrient Film Technique
DWC	Deep Water Culture
RAS	Recirculating Aquaculture System
HPS	Hydroponic system
AP	Aquaponic
COD	Chemical Oxygen Demand
ET	Evapotranspiration
CHP	Combined heat-power generator
RH	Relative Humidity
DAPS	Decoupled Aquaponic System
TSS	Total Suspended Solids
DM	Dry matter
NUE	Nutrient use efficiency
WUE	Water use efficiency
N	Nitrogen
P	Phosphorus

List of symbols

Symbol	Definition
α	mass fraction of fish sludge water that will end up in the waste sludge
β	mass fraction of feed (dry matter) that ends up in the RAS water as solids
γ	mass fraction of fish sludge water that is present in the effluent
η_{bf}	efficiency of the biofilter
δ	mass fraction of feed input ingested by fish
ϵ	mass fraction of ingested N that is excreted as TAN
ζ	mass fraction of ingested P retained by fish
ξ	mass fraction of ingested N that is excreted as feces
ι	mass fraction of N flowing into the digester that is present in the effluent
κ	mass fraction of ingested COD retained by the fish
λ	mass fraction of ingested COD that is excreted as feces
μ	biogas yield per mass unit of COD
u	energy density of methane
η_{gen}	energy conversion efficiency of the generator
c	concentration
p	production
Q	volumetric flow rate
m	mass
$\dot{m}$	mass flow rate
S	sensitivity

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1. Introduction

Increasing worldwide population is predicted to cause problems in the future, such as maintaining food security, increasing pollution and decreasing resources. Water, nutrients, and energy are becoming scarcer, resulting in increasing prices. Also in Kenya, water scarcity is already a pressing problem. However, on top of that, it is leading to insufficient food production as well, having millions of Kenyans face starvation (BBC, 2017). Insufficient food production due to water scarcity asks for sustainable food production methods, and aquaponics (AP) might be one of those methods. Close to the city of Nairobi, Kenya, the KeniAP project is set up to design an aquaponic system that produces food (fish and vegetables) in a sustainable way, especially with regards to nutrient and water use.

1.1 Background

The KeniAP system, which can be seen in Figure 2, is regarded in this research study. To understand the system, some basic knowledge on aquaponics is required.

Aquaponics is a combination of aquaculture, the cultivating of aquatic animals or plants for food, and hydroponics, in which plants are grown without soil and nutrients are dissolved in water.
Whereas multiple types of aquaculture systems exist, only a recirculating aquaculture system (RAS), containing fish, is considered in this research study. An unwanted trait of a RAS is the accumulation of waste, consisting of organic matter and nutrients, to levels that are toxic to fish (Rakocy *et al*., 2006), which has to be counteracted by different types of filters. Mechanical filters can be used to partly capture the solids in the water stream, such as feces or uneaten feed. Different types of mechanical filters include settling basins, screen filters or drum filters. However, not all waste in the system is solid. Part of the waste is soluble, of which nitrogenous waste is the main toxic part, especially ammonia and nitrite (Timmons and Ebeling, 2010). Biofilters are used to remove this waste from the system, in which ammonia is first oxidized into nitrite, and then into nitrate. Nitrate can also be toxic to fish, but concentrations can be much higher than for ammonia and nitrite before toxic levels are reached. Different types of biofilters include a moving bed biofilm reactor (MBBR) or a trickling filter. Fish produce carbon dioxide, which will become a limiting factor of production when concentrations increase. Gas exchange is necessary to remove carbon dioxide from the water and transfer oxygen into the water. At higher stocking densities, the natural gas exchange is not sufficient (Timmons and Ebeling, 2010), in which case a trickling filter is an option that offers higher levels of gas exchange. Fish are harvested when the maximum stocking density is reached.
In hydroponics, plants are grown without soil, and nutrients are dissolved in water, as opposed to conventional plant production where nutrients are added to the soil. Substrates, such as rock wool, if necessary combined with a wire, provide the stability that is normally provided by soil. The most distinguishable property for different types of hydroponic systems is the way plant roots are in contact with the water/nutrient solution. In Deep Water Culture (DWC), plants are grown in tanks or troughs with a water depth of 5 centimeters or more. In Nutrient Film Technique (NFT) systems, the nutrient solution is just a thin layer, also known as a film. The nutrient solution circulates between ditches, in which the plants are grown, and a storage tank, where additional nutrients are added if necessary, thus creating a hydroponic system (HPS).

By combining aquaculture with hydroponics, the waste of the RAS can be used as a nutrient source for the hydroponic system, thus reducing the need for adding nutrients from an external source. Therefore, fish feed is the source of nutrients for both plant and fish production. Water from the RAS is pumped to the HPS, where part of the dissolved nutrients are available for plant production, lowering the nutrient concentration in the water, since plants assimilate nutrients. In a RAS, fresh water is mixed with RAS water to ensure proper water quality for the fish. In an aquaponic system, the need for fresh water might be reduced, since plants remove waste from the water. This characteristic of an aquaponic system asks for a system in which the water is circulating between RAS and HPS, which is a coupled aquaponic system. However, optimal water conditions for the hydroponic and aquaculture part of the system are different, although they may overlap in some cases. A different approach is a decoupled aquaponic system (DAPS), in which water is not circulating between the RAS and HPS. Fish water is moved from the RAS to the HPS to remove nutrients from the RAS water, and increase nutrient concentrations in the nutrient solution of the HPS. Since the water does not move back to the RAS, there is no circulation and the two systems are decoupled. An advantage of this design is that water characteristics can be optimized for each separate production system (Kloas *et al*., 2015). However, water usage is higher than in a coupled aquaponic system. Plant assimilation is no longer used as a means of lowering nutrient concentrations to achieve fish water requirements, which means more fresh water is necessary to meet these requirements. To increase efficient use of water, research is performed into methods of capturing evapotranspiration water (Dannehl *et al*., 2014).

Sustainability of a DAPS can be improved by introducing an anaerobic digester to the system. The captured solids from the mechanical filter consist of organic, chemically oxidizable matter. This stream of suspended solids, referred to as fish sludge, can be used as feedstock for a digester. Anaerobic digestion converts the organic matter into biogas, waste sludge, and wastewater. The produced biogas can be converted into energy using a heat and power generator. Generated electricity can on its turn be used to (partly) power the system. Waste sludge consists of organic matter that could not be digested by microbes, but could still be used as fertilizer on an open field. Wastewater is the liquid residual waste stream, referred to as effluent, which has a positive impact on plant growth since the digestion process remobilizes nutrients (Goddek *et al*., 2016) and can thus be used by plants in the HPS. Chemical oxygen demand (COD) indicates the amount of oxygen necessary to break down organic matter, and is generally used to calculate biogas yields (Lier *et al*., 2008).

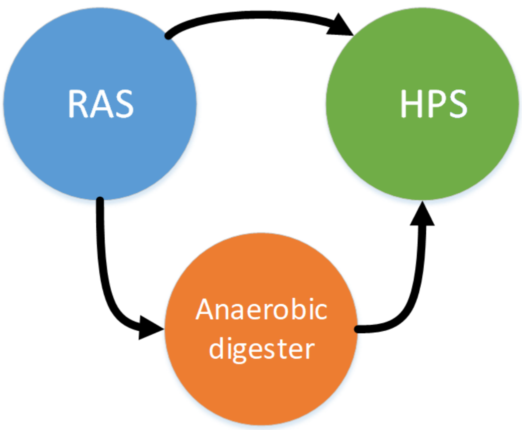

Figure 1 Simplified view of water and nutrient streams in a decoupled AP system.

In a developing country such as Kenya, a low-tech method of sustainable food production is more relevant than a high-tech method since investment costs are lower. On top of that, less complexity makes the solution easier to be adopted, provided that economic feasibility is achieved. The KeniAP system is located in Nairobi, a city with more than three million inhabitants. Production of high-value food close to customers means a shortened supply chain and a lower cost price. In a poor country, keeping food prices as low as possible is necessary to acquire or maintain food security.

1.2 Problem

Models of AP systems have been developed (Karimanzira *et al*., 2016; Lastiri *et al*., 2016; Yogev *et al*., 2016) to understand and help in designing them. Parameters used in these AP models are based on experimentally obtained values that are found in literature. Uncertainty is introduced into an AP model because uncertainty is present in experimentally obtained values, for example due to experimental errors. Moreover, one parameter value used in a model could be based on multiple experimentally obtained values, introducing additional uncertainty into an AP model due to an estimation error. No research on the effect of uncertain parameters on model outputs has yet been performed. For the KeniAP system, no model is yet available. During the course of this research study, the physical KeniAP system was built and started production. Design parameters were based on guidelines such as offered by Rakocy *et al*. (2006). Creating a model for the KeniAP system will help in optimizing the system in terms of sustainability. On top of that, the model can be used to perform an uncertainty analysis, which might be applicable to AP system models in general. Furthermore, results of this uncertainty analysis might help in designing AP systems and guide further research on the topic.

1.3 Research objective

The objective of this research study is to gain insight into the dynamics of the KeniAP system, which is necessary to facilitate optimization of the system in terms of nutrient, water, and energy use. It also embodies understanding the effect of uncertain parameters on the systems' performance in terms of nutrient, water, and energy use. The goal of aquaponics is sustainable use of nutrients, water, and energy. Therefore, in practice, the objective of this research study boils down to creating a model of nutrient and water streams, determining the energy balance of the KeniAP system, and using it to perform an uncertainty analysis and find optimal system design parameters.

1.4 Research questions

System design parameters that were initially selected are hypothesized to account for an optimally designed aquaponic system. These design parameters account for an aquaponic system consisting of a 50 m^3 RAS with a maximum stocking density of 40 kg m^{-3}, a 1500 m^2 HPS and an anaerobic digester. Evaluating this hypothesis will be guided by the following research questions.

- What is the optimal system design of the KeniAP aquaponics system in terms of nutrient, water, and energy use?
    - What is an appropriate balance-based model for designing and understanding the KeniAP system?
    - What are relevant key performance indicators of the KeniAP system?
    - What are relevant uncertain model parameters of the balance-based model of the KeniAP system in terms of nutrient, water, and energy use?
    - What is the effect of uncertain model parameters on the performance of the KeniAP aquaponics system in terms of nutrient, water, and energy use?

1.5 Approach

To gain insight into the dynamics of the KeniAP system, a model is created. Using this model, the flow of nutrients and water between different system elements can be computed. The KeniAP system consists of three main components: RAS, HPS, and digester (as in Figure 1). Available time limits the number of nutrients that are incorporated into the model. Nutrients that are taken into account are nitrogen (N) and phosphorus (P). The flow of N is relevant because some nitrogenous compounds form significant limitations of fish water characteristics. Furthermore, it is the most essential element for plant metabolism after carbon (Marschner, 2012). P is an exhaustible and scarce resource, for which is shown that sustainable use is a necessity (Ragnarsdottir *et al*., 2011). Therefore, efficient P use is detrimental to creating an environmentally sustainable aquaponic system. However, up to 60% of the P present in the fish feed can end up in the fish sludge (Seawright *et al*., 1998), which is a waste stream if no digester is present in the system. P is part of many important organic compounds within the plant, and required concentrations in the nutrient solution (Resh, 2015) are not met in simple aquaponic systems (Delaide *et al*., 2016; Rakocy *et al*., 2004). Since P is a limiting resource that asks for efficient use due to its scarcity, it is incorporated in the model. Water is incorporated in the same model since the flow of water and the flow of nutrients are connected. Nutrients are present in the water, either dissolved or as suspended solids. Understanding how water flows between different elements of the AP system gives insight into the flow of nutrients between different elements of the AP system. Apart from the sustainable use of nutrients and water, energy usage and production of the AP system also has to be determined. A COD mass balance is used to predict biogas production of the digester. Since chemically oxidizable matter is present in the water, either dissolved or as suspended solids, the COD mass balance is connected to the flow of water. Hence, the COD mass balance is integrated into the same model. Energy usage is a function of the power of the electronic devices in the entire system, and the amount of time during which these are running.

Differential mass balance equations of N, P, COD, and water make up the foundation of the model. From the mass balance of COD and the energy usage of all electronic devices in the system, an energy balance can be created. Differential mass balance equations are solved using the forward Euler method in Microsoft Excel™, the chosen software environment for implementation of the model. Constraints are added to make the model resemble reality more closely.

Model outputs that are indicators of sustainability are key performance indicators in this system. After these are defined, an uncertainty analysis and optimization of the AP system can be performed. Microsoft Excel™ is a useful tool for the uncertainty analysis and optimization since it is easy to change system parameters and results of these changes are instantly shown. For the uncertainty analysis, parameters are selected that are expected to create the most uncertainty in the model outputs or are the most uncertain in reality. Results of the uncertainty analysis will be presented by quantifying the uncertainty of the model outputs caused by uncertainty in the selected parameters. During optimization, system design parameters are selected that present the most favorable values of key performance indicators. These design parameters will be compared with the initially selected system design parameters, after which differences will be explained. In order to verify and interpret the results of both the uncertainty analysis and the optimization, they will be compared with current knowledge in literature on aquaponics.

1.6 Outline

In chapter 2, materials and methods used during this research study are presented. Results are presented in chapter 3, after which they are discussed in chapter 4. Finally, conclusions are drawn in chapter 5.

2. Materials and methods

A description of the model and the system on which it is based will be presented in this chapter. In Figure 2, an overview of the entire KeniAP system is shown. A description of the RAS (recirculating aquaculture system), HPS (hydroponic system) and anaerobic digestion unit will be presented respectively in chapter 2.1, 2.2 and 2.3. These three chapters make up the explanation of the system itself. Parameter values reported in these chapters are referred to as the nominal values, representing the nominal situation. For the model that represents the KeniAP system, a description is given in chapter 2.4.

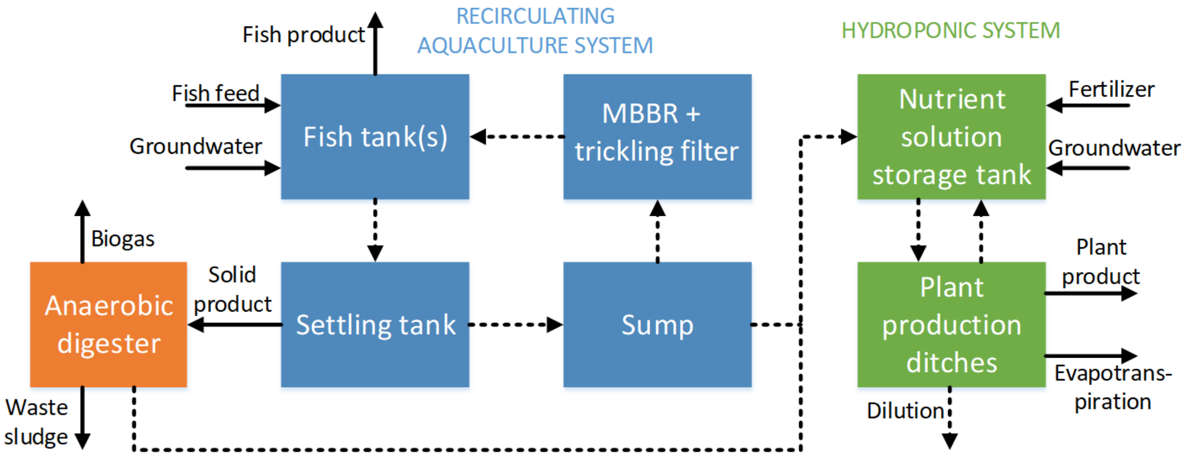

Figure 2 An overview of the KeniAP aquaponic system with all relevant material flows. Dashed lines indicate flows of water, containing nutrients. The identity of the solid lines is indicated in the figure.

2.1 Recirculating aquaculture system

The RAS, located in Nairobi, Kenya, is indoors and has a total volume of 50 m^3, equally divided over four fish tanks. Fish production is staggered, meaning that fish age is different for every tank. Maximum stocking density in the RAS in the nominal situation is 40 kg m^{-3}, which will be reached just before a tank is harvested. Nile tilapia (*Oreochromis niloticus)* enter the RAS as 1-inch fingerlings and grow for 200 days, meaning that every 50 days one tank is harvested and filled again with fingerlings. Two 1.1 kW electrical pumps and gravity are driving forces for transport of water between system elements.

2.1.1 Fish growth

Determining fish growth is required to calculate feed input, which is an essential variable to compute nutrient quantities going into the system. Feed contents and other parameters related to feed that are used in the model can be found in Table 1. Knowing that the N content of protein is 16% (Yogev *et al.*, 2016), the N content of fish feed can be computed.

Table 1 Fish feed related parameters used in the model.

Parameter	Value	Unit	Source
DM content	90%	mass fraction	(FAO, 2018)
Protein content	35%	mass fraction	(Craig and Helfrich, 2002)
P content	1.5	mass fraction	(Craig and Helfrich, 2002)
COD content	1.4	g O_2 g^{-1} DM	(Meriac, 2014)
Uneaten feed	18%	mass fraction	(Neto and Ostrensky, 2015)
Feed to TSS	25%	mass fraction of food per day	(Timmons and Ebeling, 2010)

To quantify fish growth, a model presented by Timmons and Ebeling (2010) was used. Fish length growth and subsequently weight gain was calculated using species-specific constants and water temperature, after which weight gain was determined. Required feed input was calculated using a species-specific feed conversion ratio (FCR). Ebeling and Timmons (2010) state that feed conversion ratio is variable depending on weight, presenting the ranges seen in Table 2. A function was created that meets these criteria, where FCR was calculated using fish weight (WT) as input. Data from Table 2 and expert knowledge (Goddek, 2018) leads to the conclusion that the feed conversion curve resembles a transform of a sigmoid curve:

$$y = d + \frac{a - d}{1 + \left(\frac{x}{c}\right)^{b}} \quad \textbf{Eq. 1}$$

A curve fitting tool and the data in Table 2 were used. A fitting equation for the FCR was found:

$$FCR = 1.29 + \frac{-0.548}{1 + \left(\frac{WT}{121}\right)^{6.51}} \quad \textbf{Eq. 2}$$

A curve representing this function can be found in Figure 12 in the appendices.

Table 2 Feed conversion ratio for different weight ranges of tilapia

WT (g)	FCR
< 100	0.7-0.9
> 100	1.2-1.3

Feed eaten by fish is metabolized, meaning that incoming nutrients are excreted or converted into body mass. Nutrients are excreted in solid form when they are present in fish feces, or in soluble form when they are present in fish urine. Another form of soluble nutrient excretion is that of TAN through the fish gills (Wilkie, 2002). All parameters corresponding with fish metabolism are shown in Table 3.

Table 3 Parameter values corresponding to fish metabolism as used in the model

Parameter	Value	Description	Source
Fish retention of N	35%	fraction of N in eaten feed	(Neto and Ostrensky, 2015)
Solid excretion of N	13%	fraction of N in eaten feed	(Neto and Ostrensky, 2015)
Soluble excretion of TAN	33%	fraction of N in eaten feed	(Neto and Ostrensky, 2015)
Fish retention of P	28%	fraction of P in eaten feed	(Neto and Ostrensky, 2015)
Solid excretion of P	37%	fraction of P in eaten feed	(Neto and Ostrensky, 2015)
Soluble excretion of P	17%	fraction of P in eaten feed	(Neto and Ostrensky, 2015)
COD of solid excretion	14%	fraction of COD of eaten feed	(Meriac, 2014)
COD of soluble excretion	53%	fraction of COD of eaten feed	(Meriac, 2014)

2.1.2 Fish water requirements

Successful tilapia aquaculture requires water characteristics to meet certain ranges and limits. Values for the most relevant characteristics can be found in Table 4.

Table 4 Water requirements for tilapia considered in the model

Requirement	Value	Unit	Source
Temperature	27-30	°C	(El-Sayed, 2006)
pH	7-9	-	(Ross, 2000)
Ammonia (NH_3-N)	<0.1	$mg \cdot L^{-1}$	(El-Sayed, 2006)
Nitrite (NO_2-N)	<5	$mg \cdot L^{-1}$	(DeLong *et al*., 2009)
Nitrate (NO_3-N)	<400	$mg \cdot L^{-1}$	(DeLong *et al*., 2009)

Since ammonia (NH_3) and ammonium (NH_4) are in equilibrium, TAN (total ammonia nitrogen) is used to indicate the total of these two compounds. Since the equilibrium is dependent on pH and temperature, the amount of NH_3-N can be derived when the amount of TAN is known. The temperature in the system is assumed to be constant at 29.5 °C. At lower pH, the mass fraction of TAN that is NH_3-N is lower, thus pH in the system is assumed to have a constant value of 7. Acidic or alkaline compounds are added to maintain this pH. At this temperature and pH, the fraction of TAN that is ammonia is 0.8% (Timmons and Ebeling, 2010). An MBBR and a trickling filter are present in the system, acting as a biofilter and a means for gas exchange. One 0.75 kW roots blower is responsible for pumping air into the MBBR. Biofilter TAN removal is based on the size of the biofilter (Timmons and Ebeling, 2010). For the KeniAP system, the assumption is made that the biofilter is large enough to remove 98% of TAN, converting it into nitrate. Furthermore, it was assumed that all steps of the nitrification process are taking place, meaning no nitrite is present in the system. Phosphate limits were not found to be mentioned in literature when discussing water requirements for tilapia, indicating that under normal conditions this compound will not be harmful to, nor required by tilapia. Fish water is diluted to the extent where concentrations of NO_3-N and NH_3-N are within the allowed range. Dilution happens by removing RAS water by pumping it to the HPS and replacing it with groundwater.

2.1.3 Water heating

RAS water temperature is higher than the average ambient temperature (WorldWeatherOnline, 2017), meaning heat will be lost to the surroundings. Heat loss takes place through the walls and bottom of the fish tanks, and on the water surface. On top of that, groundwater flowing into the RAS needs to be heated to the correct temperature. A groundwater temperature of 18 °C was assumed, validated by on-site experiences. Computing heat loss requires data on the RAS buildings' climate, and fish tank material characteristics, which are not available. Unreported estimations of these heat losses indicated that these are negligible compared to the heating requirement of inflowing groundwater. Heating water using solar energy would increase the systems' self-sufficiency using renewable energy. Numerous methods of solar energy collection for water heating are available (Jamar *et al*., 2016). Efficiencies of solar thermal energy collection vary, based on the type of system and climate conditions. For the KeniAP system, solar collectors are assumed to have a thermal efficiency of 50%. It has to be noted that in reality there is no water heating system present yet.

2.2 Hydroponic system

The hydroponic method utilized in the system is covering 1500 m^2. Crops are grown in troughs with a water depth of 0.5 meters, in a plastic tunnel greenhouse. Total water volume of the HPS was determined based on total crop surface and water depth in the troughs. Lettuce, *Lactuca sativa*, is grown in staggered production with a cycle duration of 75 days. Tomato, *Solanum lycopersicum*, is grown in staggered production with a cycle duration of 145 days. Lettuce and tomato both cover 50% of the total planting area.

2.2.1 Evapotranspiration

Since water loss due to evapotranspiration in the HPS needs to be replenished, evapotranspiration determines the quantity of water that is pumped from the RAS to the HPS. Nutrients present in the evapotranspiration water were assumed to be used by the plant for growth. Previous studies have used the FAO Penman-Monteith equation (Allen et al., 1998) to calculate the reference evapotranspiration rate ET_0 (Goddek and Keesman, 2018; Qiu *et al.*, 2013; S. Zolnier *et al.*, 2004). ET_o is dependent on geographical location (Nairobi, 1°28' S; 36,42'E), air temperature, relative humidity, solar radiation and greenhouse properties. Solar radiation values were obtained from Onyango and Ongoma (2015), who estimated solar radiation for Nairobi using data from a local weather station. Temperature and relative humidity were monthly average values for the period 2009-2016, which were retrieved from the web (WorldWeatherOnline, 2017). The FAO Penman-Monteith equation demands a minimum and maximum average relative humidity, whereas the previously mentioned website only provided the average relative humidity. Minimum and maximum average humidity were approximated by respectively subtracting and adding 10% to the average relative humidity. Data from the previously mentioned eight years was used to compute average weather data for one year, and can be found in the appendices, in Table 18. Greenhouse properties are specific for the KeniAP greenhouse, and were obtained from Goddek (2018), and shown in Table 25. ET_o is called the reference evapotranspiration rate since it is not yet crop specific. It is however climate and location specific, as can be deducted from the previously mentioned properties ET_o is dependent on. Thus, for the greenhouse in the KeniAP system, ET_o is constant. However, to calculate the crop specific evapotranspiration rate ET_c, ET_o is multiplied by the single crop coefficient K_c:

$$ET_c = ET_0 \cdot K_c \,. \qquad \textbf{Eq. 3}$$

K_c is dependent on crop stage, as can be seen in Figure 3.

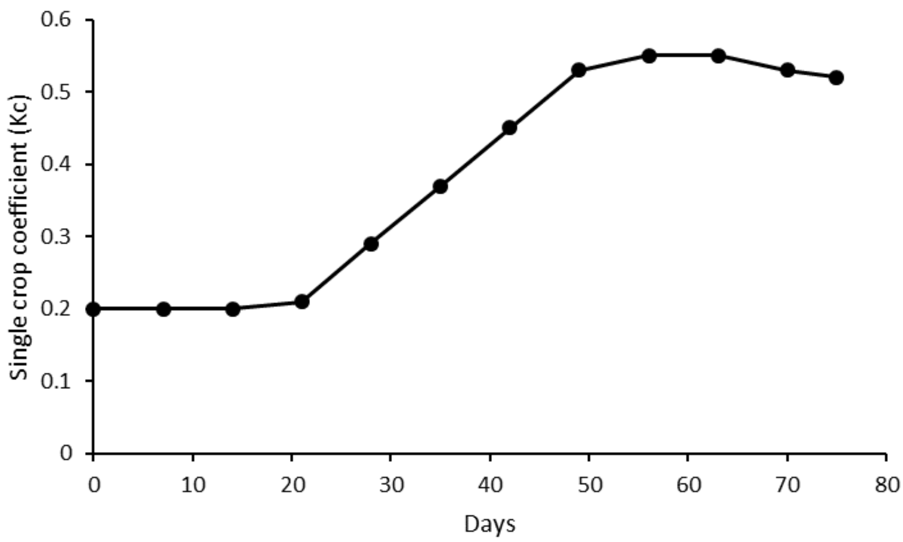

Figure 3 Crop coefficient (K_c) curve for lettuce (Allen *et al.*, 1998).

As can be deducted from Figure 3, crop specific evapotranspiration will not be constant. ET_0 was calculated for every month, after which the crop specific evapotranspiration for an entire crop cycle was calculated using Eq. 3, using just one months' ET_0 value. In the case of lettuce, the evapotranspiration during 75 days was calculated. From this, the average daily crop specific evapotranspiration rate was determined, which is justified due to the fact that crop production is staggered. Because ET_0 is different for every month, crop specific evapotranspiration will still fluctuate throughout the year, as seen in Figure 11 in the appendices. In this figure it is visible that total evapotranspiration follows a 365 day pattern, from which can be deduced that ET_o is the only cause of fluctuation of evapotranspiration in the system. Data was smoothed to improve the resemblance with reality.

2.2.2 Nutrient solution requirements

It was assumed that crop production for both tomato and lettuce is constant when nutrient concentrations are within optimal ranges. This assumption simplifies performing the uncertainty analysis, which will be discussed later. Optimal nutrient concentrations are different for tomato and lettuce. In literature, there is significant variation in the concentrations of nutrients in the nutrient solutions of hydroponic systems.

Nitrate-nitrogen concentration does not seem to have an impact on plant growth. Letey *et al.* (1982) performed an experiment where hydroponically grown lettuce was growing on nutrient solutions with nitrate-nitrogen concentrations ranging from 5 to 105 mg L^{-1}. No significant effect on plant growth was found. However, findings of Maršić and Osvald (2002) contradict this, since in their experiment a higher nitrate-nitrogen concentration resulted in significantly higher shoot weight. Resh (2015) notes that leafy vegetables such as lettuce prefer high nitrate-nitrogen levels, and suggests a nitrate-nitrogen concentration of 140 mg L^{-1}. Jones (2004) notes that nitrate-nitrogen concentration in a hydroponic nutrient solution should be between 100 and 200 mg L^{-1}, although this is not specific for lettuce.

For lettuce, the P concentration in the nutrient solution should be higher than 20 mg L^{-1} (Santos *et al.*, 2004). Jones (2004) note that the P concentration in nutrient solutions should be between 30 and 50 mg L^{-1}, adding that increasing evidence was present that this should be reduced to 10 to 20 mg L^{-1}. This advice was not specific for lettuce, but for hydroponic nutrient solutions in general.

Letey *et al.* (1982) performed the same experiment for tomato as for lettuce. As for lettuce, no significant effect on plant growth was found with different nitrate-nitrogen concentrations. However, a recommendation for nitrate-nitrogen concentration in the nutrient solution of 151 mg L^{-1} can still be found (Sonneveld and Voogt, 2009).

For P concentration of the nutrient solution for tomato, no thresholds or limits were found in literature. The optimal range will be based on target nutrient concentrations chosen by various authors. Some target P concentrations include 37 mg L^{-1} (Suhl *et al.*, 2016), 40 mg L^{-1} (Schmautz *et al.*, 2016), and 38.7 mg L^{-1} (Sonneveld and Voogt, 2009).

In the KeniAP system, both lettuce and tomato are grown using the same nutrient solution. From literature review, it was concluded that optimal nutrient concentrations are not, and cannot be exactly determined since given values are variable. Requirements for the nutrient solution in the KeniAP system, shown in Table 5, were set in a way that is generally in line with the recommended values. These requirements were confirmed to be representative of the KeniAP system (Goddek, 2018). Supplementing or diluting of the nutrient solution occurs when requirements are not met. During dilution, a certain volume of nutrient solution is removed from the system and replaced with groundwater. Replacing with groundwater instead of replacing with RAS water means that water is more efficiently used since nutrient concentrations in RAS water are higher than nutrient concentrations in groundwater. Since no data on nutrient concentrations in groundwater is available, it is assumed that no nutrients are present in groundwater. The volume of nutrient solution that is removed and replaced with groundwater is referred to as the replacement volume.

Table 5 Requirements for N and P concentration in the nutrient solution used in the KeniAP system.

Nutrient	Range
NO_3-N	100-200 mg L^{-1}
P	32-48 mg L^{-1}

2.3 Anaerobic digestion unit

An anaerobic digestion unit is present in the system to increase sustainability. Fish sludge captured by the mechanical filter is a waste stream filled with nutrients, which can be used by the system itself. Whereas a mechanical filters' purpose is to capture solids, the fish sludge stream only has a total solids content of 2.25 wt% (Mirzoyan *et al*., 2010). Mesophilic microorganisms break down the biodegradable material in this stream under the absence of oxygen, hence anaerobic. Since mesophilic microorganisms are used, a moderate temperature of 20 °C to 40 °C (Chernicharo, 2007) is required in the digester, meaning that no additional heating is required. Biogas is formed, which is a mixture of different gases. The main compound in biogas is methane, which can be used as fuel. Energy is produced by a power generator that uses this biogas as fuel. Generated electricity is used to power the pumps and the biofilter.

Several authors have used mesophilic anaerobic digestion of fish sludge to produce methane (Gebauer, 2004; Gebauer and Eikebrokk, 2006; Lanari and Franci, 1998) from which can be concluded that a methane production of 0.15 m^3 per kilogram COD can be expected. Small power generators convert biogas into electricity with an efficiency of 30%, whereas larger generators can reach an efficiency of 38% (de Mes *et al*., 2003). Since it is not sure whether a small or large generator will be used, an electrical efficiency of 35% was assumed. The amount of net energy produced by the generator was found by multiplying the generators' efficiency by the heat of combustion of methane. The reaction for the combustion of methane is as follows:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O \;, \qquad \textbf{Eq. 4}$$

in which ΔH has a value of -891 kJ $mole^{-1}$. Knowing that methane has a molar mass of 16.04 g $mole^{-1}$, it was concluded that 55.5 MJ is released per kilogram of combusted methane. Since the digester operates in a mesophilic temperature regime, the temperature of the methane is between 20 °C and 40 °C. At this temperature, methane has a density of 0.63 kg m^{-3}, thus 35.0 MJ is released for every cubic meter of combusted methane. Multiplying this by the generators' efficiency yielded a net energy yield of 12.25 MJ m^{-3}. Electric energy that is produced is used to power the pumps and the blower. If the amount of electric energy generated from biogas combustion is not sufficient, photovoltaic (PV) panels were assumed to be used to generate the remaining amount. The efficiency of these PV panels was assumed to be 15%, since this is the average efficiency of commercially sold PV panels. In reality, the remaining required amount of electric energy is drawn from the mains. The average solar radiation was computed from data in Table 18, and was used for computing both the required amount of PV-panels and solar collectors.

Apart from biogas, there are two additional outgoing streams from the digester that were considered in this research study: waste sludge and effluent, of which the latter can also be referred to as supernatant. Anaerobic digestion effluent is a water stream in which the remainder of the nutrients that are not used in the digestion process is present. These nutrients are mobilized due to remineralization happening in the digester, meaning that they are readily available for the plants (Goddek *et al*., 2016). Up to 90% of P going into the digester can be present in the effluent (Jung and Lovitt, 2011). From expert knowledge (Goddek, 2018) followed the assumption that 25% of ingoing nitrogen is present in the effluent. Solids present in the sludge will settle to the bottom of the digester and effluent is captured from the top of the digester (Chernicharo, 2007). Based on this fact the assumption was made that 95% of the water present in the inflowing fish sludge is present in the effluent outflow.

2.4 Model description

Mass, water, and energy balances were used to create the model. Conversion factors of processes were taken from literature. State variables of the system are only a function of time, hence the system is homogeneous. The differential equations were later solved numerically using the forward Euler method, in Microsoft Excel™.

2.4.1 Water balance

A volume balance for water of the entire system is relevant since it determines the flow of nutrients and provides insight on water use:

$$\frac{dV^{water}}{dt} = Q_{gw} - Q_{ET} - \alpha \cdot Q_{SW} - Q_{dl}^{HPS}, \qquad \textbf{Eq. 5}$$

in which V^{water} is the total volume of water in the system, Q_{gw} is the volumetric flow rate of inflowing groundwater in the AP system, Q_{ET} the volumetric flow rate of evapotranspiration water, Q_{SW} the volumetric flow rate of fish sludge water, and Q_{dl}^{HPS} the volumetric flow rate of water removed during dilution of the nutrient solution. Parameter α represents the fraction of fish sludge water that ends up in the waste sludge, thus leaving the system.

From the fact that the water level in the AP system is constant can be derived that

$$\frac{dV^{water}}{dt} = 0\,. \qquad \textbf{Eq. 6}$$

Q_{ET} is computed using the FAO-Penmann Monteith equation, as described in chapter 2.2.1.

The volumetric flow rate of fish sludge water at time t is defined as

$$Q^{SW}(t) = \frac{\dot{m}_{feed}(t) \cdot c_{feed}^{DM} \cdot \beta \cdot \dfrac{1 - w_{sludge}^{TS}}{w_{sludge}^{TS}}}{\rho_{water}}, \qquad \textbf{Eq. 7}$$

in which $\dot{m}_{feed}(t)$ is the mass flow rate of feed at time t,c_{feed}^{DM} is the mass fraction of dry matter in feed, β is the mass fraction of feed (dry matter) that ends up in the RAS water as solids, of which the value can be found in Table 1, w_{sludge}^{TS} is the mass fraction of solids in fish sludge, and ρ_{water} is the density of the fish water.

The computation of dilution of the nutrient solution is defined as

$$V_{dl}^{HPS}(t) = \max \frac{m_{HPS}^{x}(t) - c_{HPSmax}^{x} \cdot V_{HPS}}{c^{x}(t) - c_{gw}^{x}}, \quad if\ c(t) > c_{max}^{x}\,, \qquad \textbf{Eq. 8}$$

in which $V_{dl}^{HPS}(t)$ is the replacement volume at time t, $m_{HPS}^{x}(t)$ the mass of nutrient x in the nutrient solution at time t, c_{HPSmax}^{x} the maximum mass concentration of nutrient x in the nutrient solution, V_{HPS} the total volume of the nutrient solution, $c^{x}(t)$ the mass concentration of nutrient x in the nutrient solution at time t, and c_{gw}^{x} the mass concentration of compound x in groundwater. Nutrient x is either N or P.

The volume balance of water for the RAS is defined as

$$\frac{dV_{RAS}^{water}}{dt} = Q_{gw}^{RAS} - Q_{SW} - Q_{dl}^{RAS} - Q_{refill}^{HPS}, \qquad \textbf{Eq. 9}$$

in which V_{RAS}^{water} is the total volume of water in the RAS, Q_{gw}^{RAS} is the volumetric flow rate of groundwater flowing into the RAS, Q_{dl}^{RAS} the volumetric flow rate of water flowing out of the RAS to the HPS when RAS water is diluted, and Q_{refill}^{HPS} the volumetric flow rate of water flowing from the RAS to the HPS to keep the water level in the HPS constant.

From the fact that the water level in the RAS is constant can be derived that

$$\frac{dV_{RAS}^{water}}{dt} = 0\,. \qquad \textbf{Eq. 10}$$

The required water replacement volume in the RAS at time t is defined as

$$V_{dl}^{RAS}(t) = \max \frac{m_{RAS}^{x}(t) - c_{RASmax}^{x} \cdot V_{HPS}}{c_{RAS}^{x}(t) - c_{gw}^{x}}, \qquad \textbf{Eq. 11}$$

in which $V_{dl}^{RAS}(t)$ is the replacement volume at time t, $m_{RAS}^{x}(t)$ the mass of compound x in the RAS water at time t, c_{RASmax}^{x} the maximum allowed mass concentration of compound x in the RAS water, $c_{RAS}^{x}(t)$ the mass concentration of compound x in the RAS water at time t. Compound x is either NH_3-N or NO_3-N.

The water volume balance of the HPS is defined as

$$\frac{dV_{HPS}^{water}}{dt} = Q_{refill}^{HPS} + Q_{gw}^{HPS} + Q_{dl}^{RAS} + Q_{ANA} - Q_{ET} - Q_{dl}^{HPS}, \qquad \textbf{Eq. 12}$$

in which V_{HPS}^{water} is the total volume of the nutrient solution, Q_{gw}^{HPS} is the volumetric flow rate of groundwater into the nutrient solution, being equal to the volumetric flow rate Q_{dl}^{HPS} out of the nutrient solution during dilution, and Q_{ANA} the volumetric flow rate of effluent from the anaerobic digester into the nutrient solution. From the fact that the water level in the HPS is constant can be derived that

$$\frac{dV_{HPS}^{water}}{dt} = 0\,. \qquad \textbf{Eq. 13}$$

Q_{ANA} is defined as

$$Q_{ANA}(t) = \gamma \cdot Q_{SW}(t), \qquad \textbf{Eq. 14}$$

in which γ is the fraction of fish sludge water that is present in the effluent, of which the value can be found in chapter 2.3.

2.4.2 Nitrogen, phosphorus, and COD mass balances

In the following section mass balances for N, NO_3-N, TAN, and P in the RAS and HPS are shown using differential equations. In the RAS, N flows into the system as feed but is divided into NO_3-N and TAN due to fish metabolism.

The mass balance for NO_3-N in the RAS is defined as

$$\frac{dm_{RAS}^{NO_3-N}}{dt} = p^{TAN} \cdot \eta_{bf} + Q_{gw}^{RAS} \cdot (c_{gw}^{NO_3-N} + \eta \cdot c_{gw}^{TAN}) - \left(Q_{\mathrm{SW}} + Q_{dl}^{RAS} + Q_{refill}^{HPS}\right) \cdot c_{RAS}^{N-NO_3} \,, \qquad \textbf{Eq. 15}$$

in which $m_{RAS}^{NO_3-N}$ is the mass of NO_3-N in the RAS water, p^{TAN} the production of TAN by fish, $c_{gw}^{NO_3-N}$ the mass concentration of NO_3-N in groundwater, and $c_{RAS}^{NO_3-N}$ the mass concentration of NO_3-N in the RAS water. Parameter η_{bf} represents the efficiency of the biofilter, thus the percentage of TAN that is nitrified.

Fish production of TAN is defined as:

$$p^{TAN}(t) = \dot{m}_{feed}(t) \cdot w_{feed}^{N} \cdot \delta \cdot \epsilon \,, \qquad \textbf{Eq. 16}$$

in which c_{feed}^{N} is the mass fraction of N in fish feed, δ is the fraction of feed ingested by fish, and ϵ the fraction of N eaten by the fish that is excreted as TAN.

The mass balance for TAN in the RAS is defined as

$$\frac{dm_{RAS}^{TAN}}{dt} = p^{TAN} \cdot \left(1 - \eta_{bf}\right) + Q_{gw}^{RAS} \cdot c_{gw}^{TAN} \cdot (1 - \eta_{bf}) - \left(Q_{\mathrm{SW}} + Q_{dl}^{RAS} + Q_{refill}^{HPS}\right) \cdot c_{RAS}^{TAN} \,, \qquad \textbf{Eq. 17}$$

in which m_{RAS}^{TAN} is the mass of TAN in the RAS water, c_{gw}^{TAN} the mass concentration of TAN in groundwater, and c_{RAS}^{TAN} the mass concentration of TAN in the RAS water.

The mass balance for P in the RAS is as follows:

$$\frac{dm_{RAS}^{P}}{dt} = \dot{m}_{feed}(t) \cdot w_{feed}^{P} \cdot (1 - \zeta) + Q_{gw}^{RAS} \cdot c_{gw}^{P} - \left(Q_{SW} + Q_{dl}^{RAS} + Q_{refill}^{HPS}\right) \cdot c_{RAS}^{P} \,, \qquad \textbf{Eq. 18}$$

in which m_{RAS}^{P} is the mass of P in the RAS water, w_{feed}^{P} is the mass fraction of P in feed, ζ is the mass fraction of ingested P retained by fish, c_{gw}^{P} is the mass concentration of P in groundwater, and c_{RAS}^{P} is the mass concentration of P in RAS water.

In the HPS, total N is regarded instead of nitrate-nitrogen and TAN. The mass balance of N in the HPS is defined as

$$\frac{dm_{HPS}^{N}}{dt} = (Q_{dl}^{RAS} + Q_{refill}^{HPS}) \cdot \left(c_{RAS}^{NO_3-N} + c_{RAS}^{TAN}\right) + Q_{ANA} \cdot c_{ANA}^{N} + Q_{dl}^{HPS} \cdot (c_{gw}^{NO_3-N} + c_{gw}^{TAN}) + \dot{m}_{supp}^{N} - \left(Q_{dl}^{HPS} + Q_{ET}\right) \cdot c_{HPS}^{N} \,, \qquad \textbf{Eq. 19}$$

in which m_{HPS}^{N} is the mass of N in the nutrient solution, c_{ANA}^{N} is the mass concentration of N in the effluent of the anaerobic digester, $\dot{m}_{supp}^{N}$ is the mass flow rate of N supplement into the nutrient solution, and c_{HPS}^{N} is the mass concentration of N in the nutrient solution.

The mass flow rate of nutrient x supplement at time t is defined as

$$\dot{m}_{supp}^{x}(t) = \frac{V_{HPS} \cdot c_{HPSmin}^{x} - m_{HPS}^{x}(t)}{T} \,, \quad if\ c_{HP}^{x} < c_{HPmin}^{x} \,, \qquad \textbf{Eq. 20}$$

in which $\dot{m}_{supp}^{x}(t)$ is the mass flow rate of nutrient x supplement flowing into the nutrient solution at time t, c_{HPSmin}^{x} the minimum required mass concentration of nutrient x in the nutrient solution, $m_{HPS}^{x}(t)$ the mass of nutrient x in the nutrient solution at time t, and T the time period during which the supplement is added to the nutrient solution. Nutrient x is either N or P.

$c_{ANA}^{N}(t)$ can be computed using

$$c_{ANA}^{N}(t) = \frac{\left(\left(\dot{m}_{feed}(t) \cdot c_{feed}^{N}\right) \cdot (1 - \delta + \xi \cdot \delta) + Q_{SW}(t) \cdot \left(c_{RAS}^{NO_3-N}(t) + c_{RAS}^{TAN}(t)\right)\right) \cdot \iota}{Q_{ANA}(t)}, \quad \textbf{Eq. 21}$$

in which ξ is the fraction of ingested N that is excreted as feces, and ι is the fraction of N flowing into the digester that is present in the effluent.

The mass balance of P in the HPS is as follows:

$$\frac{dm_{HPS}^{P}}{dt} = (Q_{dl}^{RAS} + Q_{refill}^{HPS}) \cdot (c_{RAS}^{P}) + Q_{ANA} \cdot c_{ANA}^{P} + Q_{dl}^{HPS} \cdot c_{gw}^{P}) + \dot{m}_{supp}^{P} - \left(Q_{dl}^{HPS} + Q_{ET}\right) \cdot c_{HPS}^{P}, \quad \textbf{Eq. 22}$$

in which m_{HPS}^{P} is the mass of P in the nutrient solution, c_{ANA}^{P} is the concentration of P in the effluent of the anaerobic digester, $\dot{m}_{supp}^{P}$ the mass flow rate of P fertilizer into the nutrient solution, and c_{HPS}^{P} the concentration of P in the nutrient solution.

A mass balance for COD present in the RAS is relevant since it is required to determine the amount of COD flowing to the anaerobic digester:

$$\frac{dm_{RAS}^{COD}}{dt} = Q_{gw}^{RAS} \cdot c_{gw}^{COD} + \dot{m}_{feed} \cdot w_{feed}^{COD} \cdot (1 - \delta \cdot \kappa) - \left(Q_{SW} + Q_{dl}^{RAS} + Q_{refill}^{HPS}\right) \cdot c_{RAS}^{COD}, \quad \textbf{Eq. 23}$$

in which m_{RAS}^{COD} is the mass of COD in the RAS water, c_{gw}^{COD} the concentration of COD in groundwater, w_{feed}^{COD} the mass fraction of COD in feed, κ the fraction of ingested COD retained by the fish, and c_{RAS}^{COD} the concentration of COD in the RAS water. From this equation, the flow of COD to the digester $\dot{m}_{dig}^{COD}$ can be derived:

$$\dot{m}_{dig}^{COD}(t) = \dot{m}_{feed}(t) \cdot w_{feed}^{COD} \cdot \left((1 - \delta) + \delta \cdot \lambda\right) + Q_{SW}(t) \cdot c_{RAS}^{COD}(t), \quad \textbf{Eq. 24}$$

in which λ is the fraction of ingested COD that is excreted as feces.

2.4.3 Energy balance

Methane produced in the anaerobic digester will be converted into energy using a generator. Energy is consumed by two identical pumps and a blower in the biofilter. The pumps and the blower are running constantly at a constant consumption level. From this information, the energy balance can be drawn:

$$\frac{dE}{dt} = p_{gen}^{E} + p_{sol}^{E} + p_{PV}^{E} - 2 \cdot P_{pump} - P_{blower} - Q_{gw}^{E}, \quad \textbf{Eq. 25}$$

in which p_{gen}^E is the production of electric energy by the generator, p_{sol}^E the production of solar thermal energy, p_{PV}^E the production of solar electric energy, P_{pump}^E the power of the pump, P_{blower}^E the amount of energy used by the blower, and Q_{gw}^E the rate of heat flow to the inflowing groundwater in the RAS.

Since the system is supposed to be self-sufficient, it can be stated that

$$\frac{dE}{dt} = 0 \,. \qquad \textbf{Eq. 26}$$

The production of energy by the anaerobic digester is defined as

$$p_{gen}^E(t) = \dot{m}_{dig}^{COD}(t) \cdot \mu \cdot u \cdot \eta_{gen} \qquad \textbf{Eq. 27}$$

in which μ is the biogas yield per mass unit of COD, u is the energy density of methane, and η_{gen} is the energy conversion efficiency of the generator.

The production of solar thermal energy can be computed using

$$p_{sol}^E = \overline{R_s} \cdot A_{sp} \cdot \eta_{sp} \,, \qquad \textbf{Eq. 28}$$

in which $\overline{R_s}$ is the average solar radiation computed from data in Table 18 in the appendices, A_{sp} the total surface of the solar collectors, and η_{sp} the thermal efficiency of the solar water heating system.

Electric energy is produced using PV panels, of which the quantity of production is defined as

$$p_{PV}^E = \overline{R_s} \cdot A_{PV} \cdot \eta_{PV} \,, \qquad \textbf{Eq. 29}$$

in which A_{PV} is the surface area of the PV-panels, and η_{PV} is the efficiency of the PV-panels.

The rate of heat flow to the inflowing groundwater in the RAS is as follows:

$$Q_{gw}^E(t) = Q_{gw}^{RAS}(t) \cdot c_p \cdot \rho \,, \qquad \textbf{Eq. 30}$$

in which c_p is the specific heat of groundwater, and ρ the density of groundwater.

2.4.4 Model design

The differential equations are solved numerically in Microsoft Excel™ by using the Euler forward method, with a step size Δt of one day. Solving differential equations numerically using the Euler forward method is a practical and simple way to approximate the solution of differential equations, at the cost of small deviations (errors) from the actual solution.

First, the daily required amount of feed is calculated using the data and methods described in chapter 2.1.1, and the daily amount of evapotranspiration water is calculated using the data and methods described in chapter 2.2.1. The order of calculation steps taken to numerically solve the water balance differential equations can be found in Table 19 in the appendices. The order of calculation steps taken to numerically solve the mass balance differential equations of N, NO_3-N, TAN can be found in Table 20 in the appendices. The order of calculation steps taken to numerically solve the mass balance differential equations of P and COD can be found respectively in Table 21 and Table 22 in the appendices. The order of calculation steps taken to numerically solve the energy balance can be found in Table 23 in the appendices. In view of time constraints, assumptions were made in order to make certain processes and issues negligible.

1) Whereas the mechanical filter will not catch all solids in the water, solids removal is 100%. Remaining solids will settle in the sump of the RAS, which will be cleaned periodically. The waste of this operation will be put into the digester, thus all solids will eventually end up in the digester, justifying the assumption of 100% solid removal.
2) Water temperatures in the RAS and HPS are constant.
3) Since fish and plant production are staggered, they are constant as long as fish water and nutrient solution requirements are met.
4) The amount of a nutrient taken up by the plants is equal to the amount of that nutrient present in evapotranspiration water (Goddek, 2018).
5) Nutrient concentration thresholds and limits for plants are constant throughout the entire plant cycle.
6) Water retention by fish and plants is neglected. Water leaving the RAS due to fish retention is no more than the maximum stocking density per 200 days, which in this case is 40 kg m^3 per 200 days. Water leaving the HPS due to plant retention of tomato plants is no more than 17 kg m^{-2} per 145 days (Schmautz *et al*., 2016), and due to plant retention of lettuce is no more than 7 kg m^{-2} per 75 days (Touliatos *et al*., 2016). Both these numbers are small compared to the loss of water due to evapotranspiration and dilution, justifying the assumption.
7) Water entering the system due to its presence in the feed is neglected. DM content in the feed is high, and daily feed input is small compared to daily groundwater input.
8) NO_3-N, TAN, P, and COD concentrations in groundwater are zero. No measurements are performed on groundwater on the site. The assumption is justified by the fact that the site is a rural location, meaning contamination of groundwater is unlikely.

2.4.5 Uncertainty analysis

By performing an uncertainty analysis, the uncertainty of model outputs due to the uncertainty of model inputs, the parameter values, was investigated. Parameters used in this model are based on experimentally obtained values that are found in literature. Uncertainty is introduced into the model because uncertainty is present in experimentally obtained values, for example due to experimental errors. Moreover, one parameter value used in the model could be based on multiple experimentally obtained values, introducing additional uncertainty the AP model due to an estimation error. The final set of parameter values chosen for the KeniAP model, referred to as nominal values, aims to represent reality as closely as possible. An uncertainty analysis sheds light on uncertainty in the model outputs resulting from uncertainty in the model parameters, might help in designing AP systems, and possibly guides further research on the topic of aquaponics.

Controlled variables and disturbance variables make up the state of a system (Keesman, 2011). Although controlled variables can be manipulated and disturbance variables cannot, there might be uncertainty present in both types of variables. In the KeniAP model, examples of disturbance variables are weather and fish metabolism parameters. Controlled variables, for example, are the stocking density or the nutrient mobilization rate (Goddek and Delaide, 2018) of the digester. Note that although the nutrient mobilization rate can be manipulated, there is no full control over this parameter, meaning that uncertainty is still present in this parameter.

A selection of parameters involved in the uncertainty analysis was made based on their uncertainty in reality and relevance for the KeniAP model (Goddek, 2018). Uncertainty is present in feed contents, which impact is checked by using extreme values for protein and P content. N and P mineralization rate of the digester have a significant impact on the system, which was confirmed by initial model runs. To show uncertainty in the model output due to the uncertainty of the mineralization rate, extreme values were selected for the fraction of N and P going into the digester ending up in the effluent. In Table 6, values used in the uncertainty analysis can be found. Protein content found in commercial product lies between 30 and 40%. For the other parameters, use of the shown minima and maxima is confirmed to be suitable for this uncertainty analysis by Goddek (2018).

Table 6 Parameters for which an uncertainty analysis was performed, along with the values used during the uncertainty analysis.

Parameter	Minimum	Maximum
Protein content	30%	40%
P in feed	1%	2%
N in effluent	10%	50%
P in effluent	10%	95%

Nominal values for RH and temperature were average values based on weather data from the period 2009-2016 (WorldWeatherOnline, 2017). To create uncertainty in the model output, the average monthly value from the period 2009-2016 that differs most from the nominal value was taken, as seen in Table 24 in the appendices.

It is uncertain whether values for fish metabolism parameters as given by Neto and Ostrensky (2015) are the same in the KeniAP system. Conditions might be different, i.e. water properties or feed properties, resulting in different values. Soluble excreted nutrients (urine and gills) and solid excreted nutrients (feces) feces both take different routes through the system, making the ratio of nutrients excreted as solubles to nutrients excreted as solids the most interesting parameter to introduce uncertainty to.

Table 7 Four uncertainty analysis scenarios (shown horizontally) where the solid:soluble excretion ratio differs from the nominal situation, either favoring solid or soluble excretion, relative to the nominal situation. Values indicate what fraction of eaten N or P is excreted solid and soluble.

Solid N excreted	**Soluble N excreted**	**Solid:soluble ratio**
8%	38%	0.211
18%	28%	0.643
Solid P excreted	**Soluble P excreted**	
30%	24%	1.25
45%	9%	5.00

In conclusion, there are 16 scenarios taken into account during the uncertainty analysis. All parameter values are set at the nominal value, except for the parameter value or parameter values investigated in a certain scenario.

A local sensitivity analysis is performed to quantify the effect of uncertainty. The following equation is used to compute the sensitivity:

$$S_y = \frac{\delta y}{\delta x} \cdot \frac{\bar{x}}{\bar{y}} \,, \quad \textbf{Eq. 31}$$

in which y is a certain model output, x a certain parameter. Since a bar accent indicates the nominal value, multiplication by $\frac{\bar{x}}{\bar{y}}$ normalizes the sensitivity value. It is not possible to compute the sensitivity to uncertain climate conditions, since these can not be captured in one parameter.

2.4.6 Key performance indicators

Since the model creates lots of data, the output of the model needs to be specified. Key performance indicators are chosen to make a clear comparison between different model outputs resulting from the uncertainty analysis. Model output is taken from day 150 to day 1149, since it is a period of 1000 days, starting at the first day in which all fish tanks are stocked.

Aquaponic systems are designed to improve efficient use of nutrients and water. In the KeniAP system, nutrients are put into the system in the form of feed or supplements. Nutrients are lost in the waste sludge of the digester or in wastewater when dilution of the nutrient solution takes place. With the sum of input streams and the sum of waste streams, an efficiency can be calculated:

$$Efficiency = \frac{\sum input - \sum waste}{\sum input} \qquad \textbf{Eq. 32}$$

When referring to the efficiency of nutrient use, NUE (nutrient use efficiency) is used. Eq. 32 also applies to WUE (water use efficiency), in which input is all groundwater used and waste is the sum of disposed water during dilution of the nutrient solution and water present in the waste sludge of the digester.

Feeding rate is used in aquaponics as a term to indicate the amount of fish feed required per day per surface area of hydroponics. Since it is widely used in aquaponics literature (Endut *et al*., 2010; Lennard, 2012; Rakocy *et al*., 2004), this unit can be used to compare the KeniAP system to other AP systems.

2.4.7 KeniAP system design optimization

Using Microsoft Excel™ enables the use of the Solver tool. The user defines the objective, variable cells, and constraints. In this case, sizing parameters were selected as variable cells, and maximizing the average of NUE P and WUE is used as the objective for the solver. NUE N is not regarded as N can be considered a non-exhaustive renewable resource. Planting area and maximum stocking density were the considered sizing parameters, respectively constrained between 500 m^2 and 5000 m^2, and 30 and 60 kg m^{-3}. Also, the use of P supplements in the HPS was constrained to zero. If no feasible solution could be found, the solution with the lowest amount of P supplement was selected.

3. Results

The results are presented in the following section, starting with an overview of system dynamics for the nominal situation. Both key performance indicator values and graphs are shown, to give insight into the dynamics of the system. For the uncertainty analysis, only key performance indicator values are presented. Finally, optimal sizing parameters are suggested.

3.1 System dynamics

Fish growth determines the amount of feed that is required, and therefore determines the amount of nutrients flowing into the system.

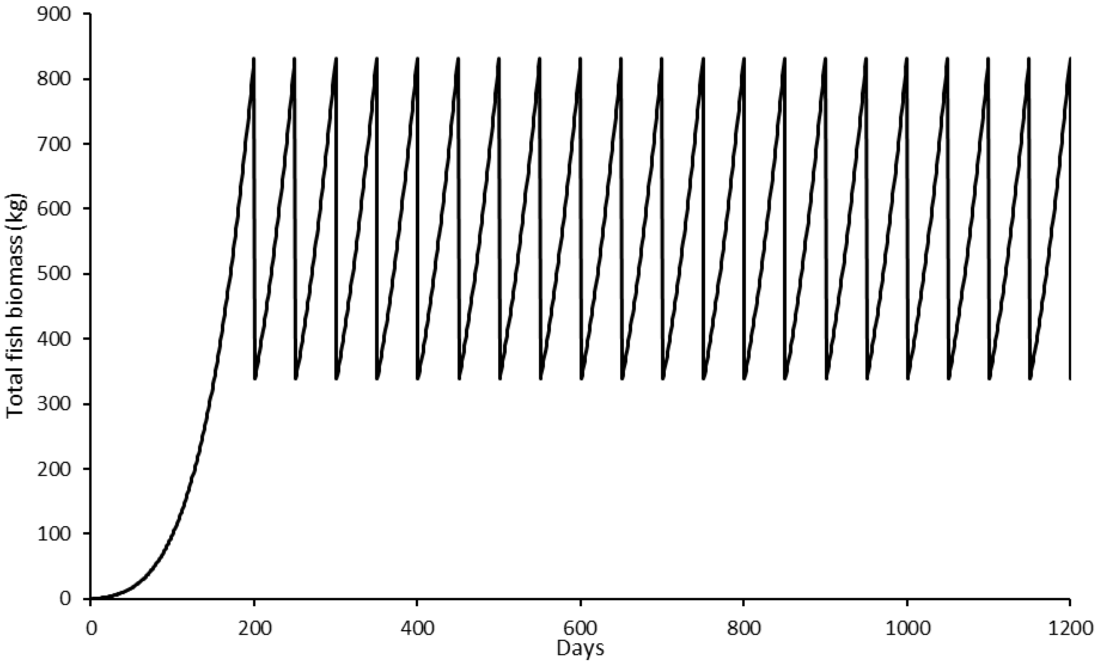

Figure 4 Total fish biomass in the KeniAP system.

Due to the method of staggered fish production, the amount of fish biomass reaches a peak every 50 days, as seen in Figure 4. Feed input, and thus nutrient input, is dependent on fish biomass in the system, meaning that nutrient input follows the same pattern, as seen in Figure 13 in the appendices. This pattern is a determining factor in the dynamics of the KeniAP system, and can, for example, be seen in Figure 5, in the concentration of nitrate-nitrogen in the RAS. Figure 4 also shows that the recurring 50-day pattern starts at day 150, explaining why it is the start of the considered period. In Figure 5, the N concentration in both the RAS and HPS is shown. For the RAS, only the nitrate-nitrogen concentration is shown. TAN concentration in the RAS is not shown, since the amount of TAN is negligible due to the high efficiency of the biofilter. Evapotranspiration is the cause of a 365-day pattern, which can also be seen in Figure 5, in the concentration of nitrate-nitrogen in the RAS. When the evapotranspiration rate is at its' highest, the most water will flow from the RAS to the HPS. In this case, nutrient concentrations in RAS water will be the lowest. N concentration in the HPS starts to drop around day 350. The explanation for this can be found in Figure 6. P reaches its' concentration limit at day 350, meaning that dilution of the nutrient solution starts occurring. P flows into the nutrient solution at a high level due to the high mobilization rate of the anaerobic digester. After every fish harvest, dilution requirement is lower, explaining why N concentration in the nutrient solution decreases at a lower rate just after fish are harvested. In contrary, P concentration in the nutrient solution increases at a lower rate just after fish harvest, because feed input, and thus P input, is lower.

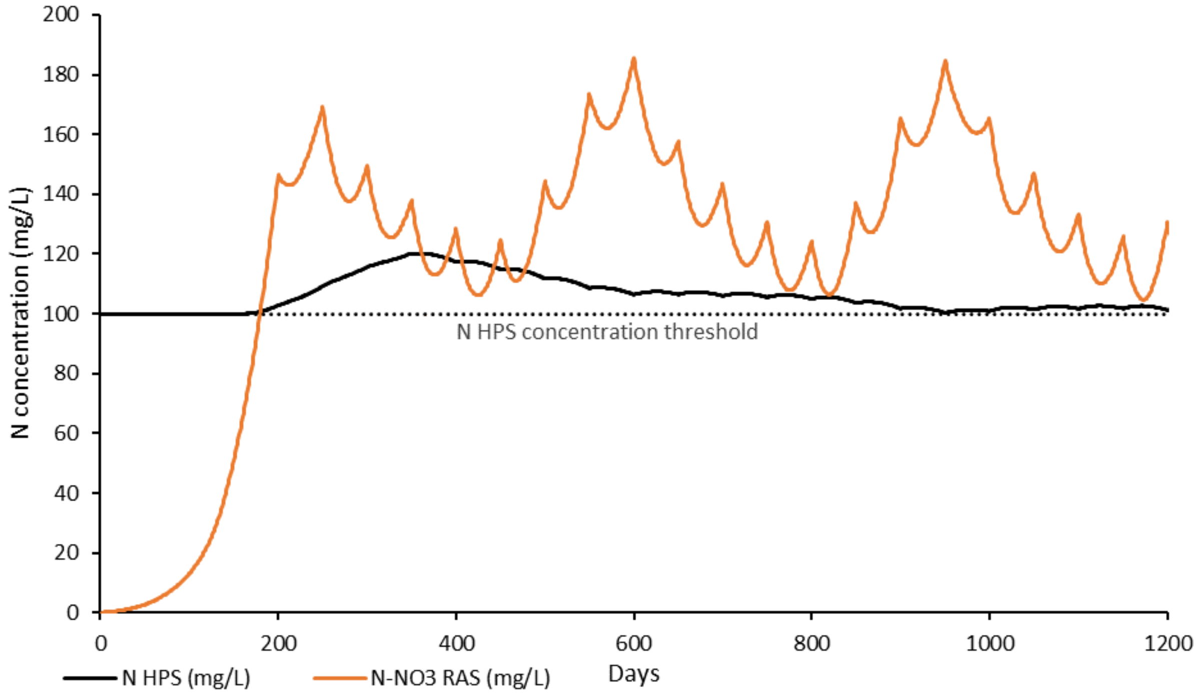

Figure 5 Nitrogen concentration in the nutrient solution, along with the concentration threshold, and nitrate-nitrogen concentration in RAS water.

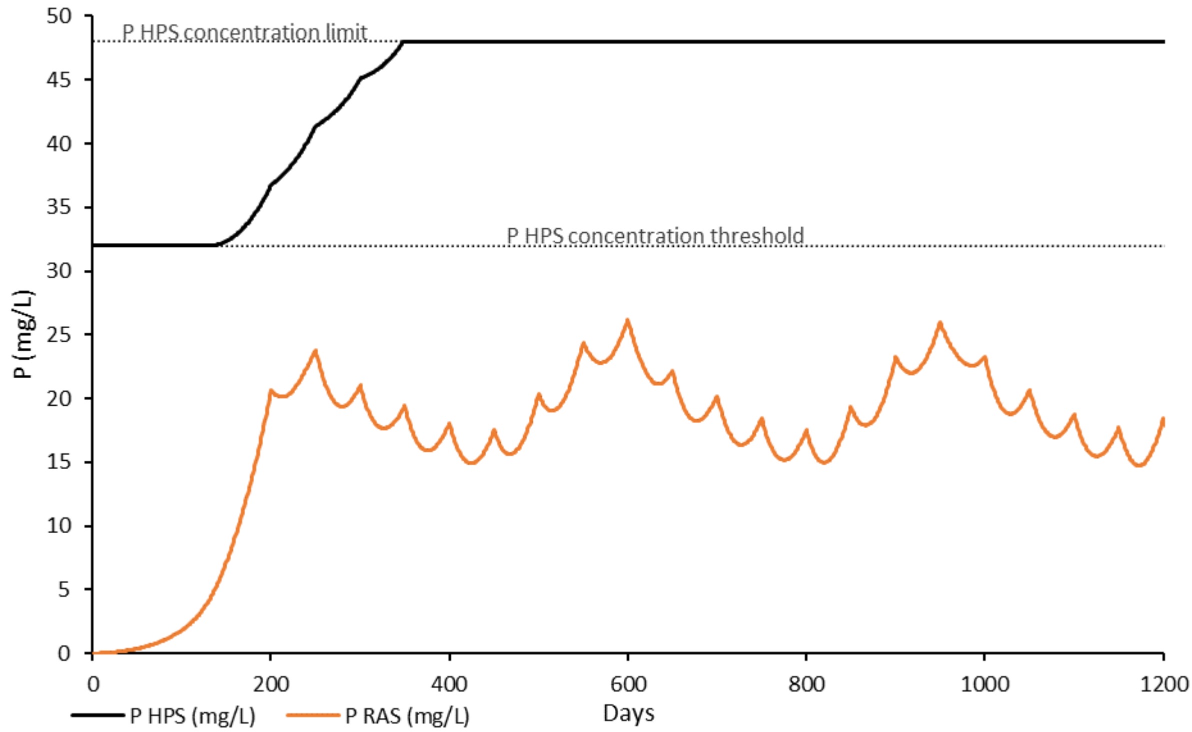

Figure 6 Phosphorus concentration in the RAS and in the nutrient solution, along with the required concentration threshold and limit for P in the nutrient solution.

P concentration in the nutrient solution is higher than in RAS water due to the fact that almost all P present in solid excretion will flow into the nutrient solution via the anaerobic digester. As mentioned before, nutrient concentrations shown in graphs are nutrient concentrations of dissolved nutrients. Both for N and P, it is visible that supplementing of nutrients is necessary during the starting phase of the system. After N and P concentrations in the RAS reach a certain level, the inflow of nutrients into the nutrient solution from the RAS is sufficient, and no supplementing is required.

Table 8 Key performance indicators and other characteristics of the KeniAP system in the nominal situation.

Parameter	Value	Unit
NUE N	65.97	%
NUE P	77.00	%
WUE	65.23	%
Feeding rate	9.08	g m^{-2} d^{-1}
Solar collector surface required	6.7	m^2
PV panel surface requirement	78.1	m^2
N in feed	763	kg
P in feed	204	kg
N supplemented	0.151	kg
P supplemented	0.000	kg

Efficient use of both nutrients and water is not achieved in the nominal situation. NUE of P is higher than NUE of N due to the significantly higher mobilization rate of P in the anaerobic digester. The fraction of nutrients originating from the supplement is negligible.

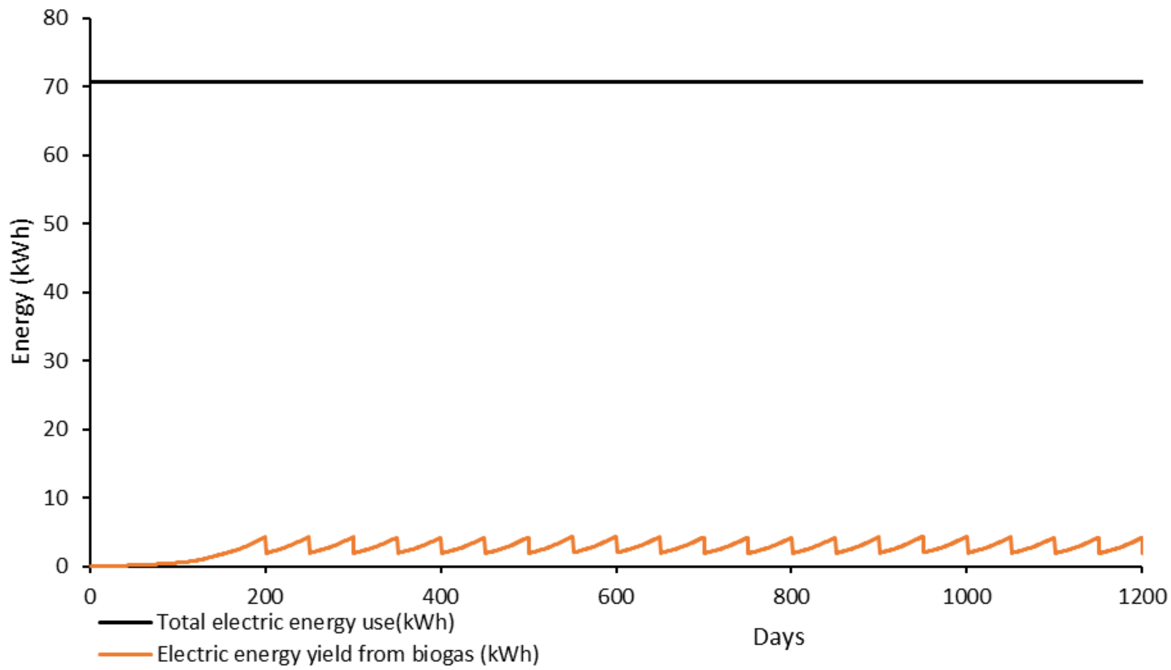

Figure 7 Total electric energy use of electronics in the AP, and electric energy produced by combustion of biogas.

Figure 7 explains why 78.1 square meters of PV panels are required. Combustion of biogas produced from fish sludge is far from sufficient in powering the system. In total, ~85 square meters of solar panels are required to produce all thermal and electric energy required by the KeniAP system.

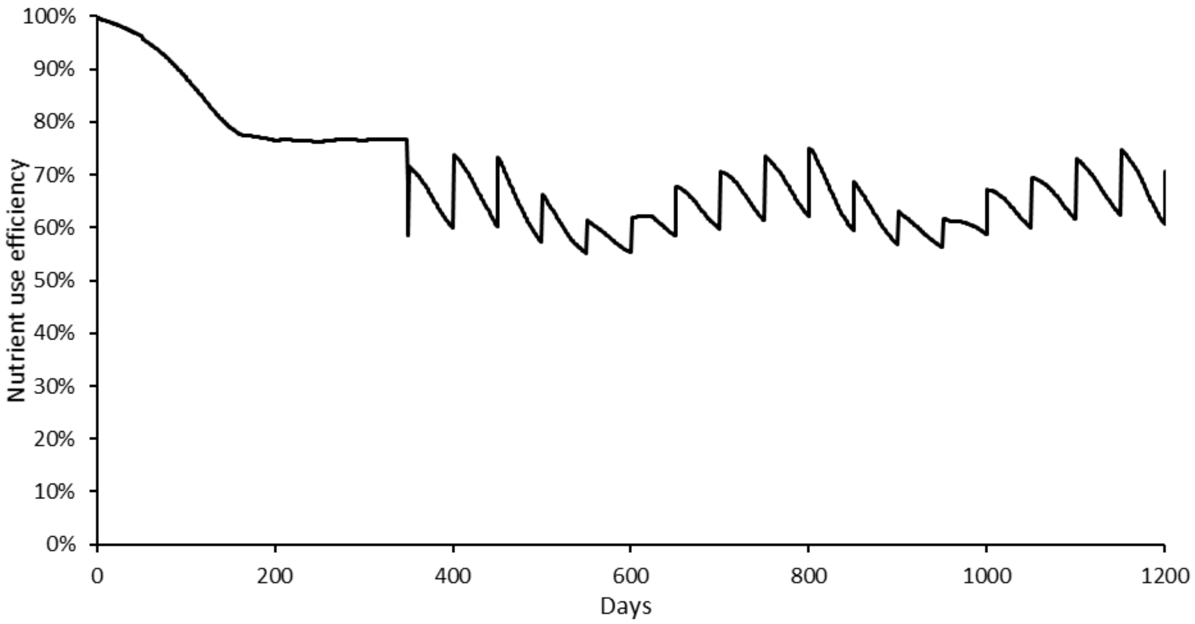

Figure 8 Nutrient use efficiency (NUE) of nitrogen in the KeniAP system.

NUE of both N and P, respectively shown in Figure 8 and Figure 9, decreases the first 200 days, of which the decrease rate is highest the first 160 days. This observation can be explained by the fact that the amount of nutrients lost in waste sludge increases until it reaches a maximum at day 200, at which point fish are harvested and feed input drops down. Supplementing N to the nutrient solution stops at ~day 160, as seen in Figure 6, explaining why NUE of N decreases at a lower rate from this day on. Supplemented nutrients are not wasted, whereas nutrients added through fish feed are partly wasted as

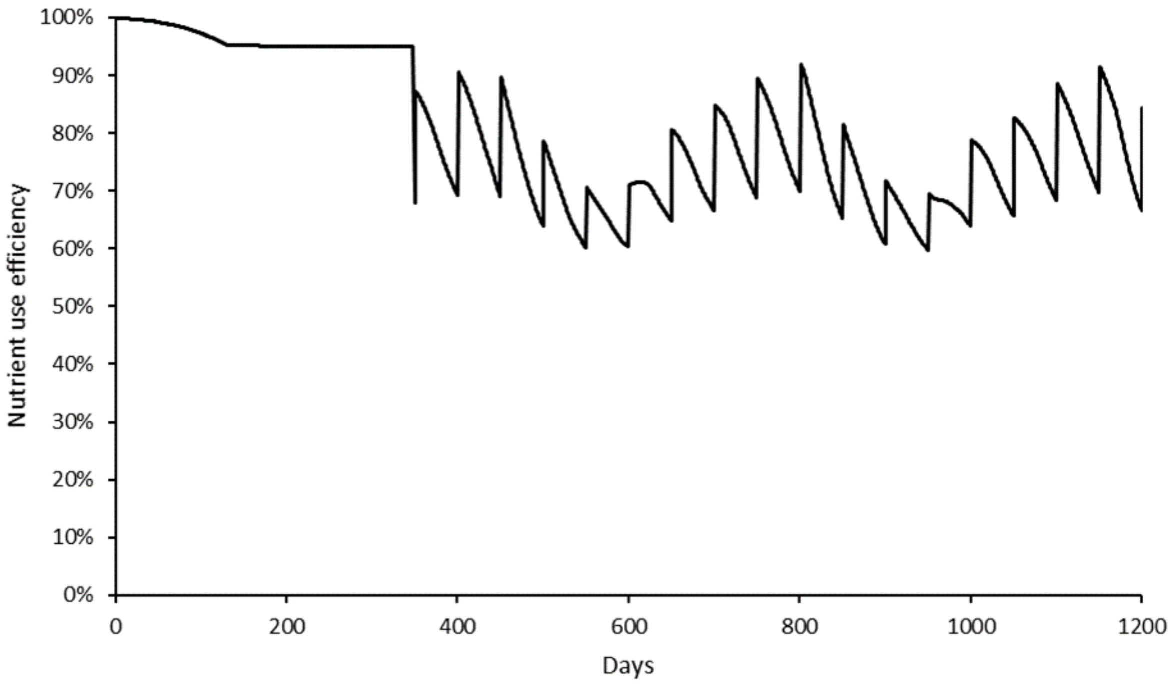

Figure 9 Nutrient use efficiency (NUE) of phosphorus in the KeniAP system.

waste sludge of the anaerobic digester. The same principle applies to NUE of P, where supplementing P to the nutrient solution stops at ~day 130, from which day on NUE P decreases at a lower rate.

At ~day 350, dilution of the nutrient solution starts to occur, causing the NUE of both N and P to drop. A 50-day pattern can also be seen in both the NUE of N and P. NUE steadily decreases, and after 50 days it instantly increases to a maximum, after which it starts steadily decreasing again. This observation is explained by the fact that after fish harvesting, the nutrient input drops down, reducing the need for dilution of the nutrient solution, as seen in Figure 14. Furthermore, a 365-day pattern can be seen in both the NUE curve of N and P. When the evapotranspiration is low, the NUE is also low, due to the fact that nutrients flowing out of the system in evapotranspiration water are not considered as wasted nutrients. If the evapotranspiration rate is low, dilution requirement is high.

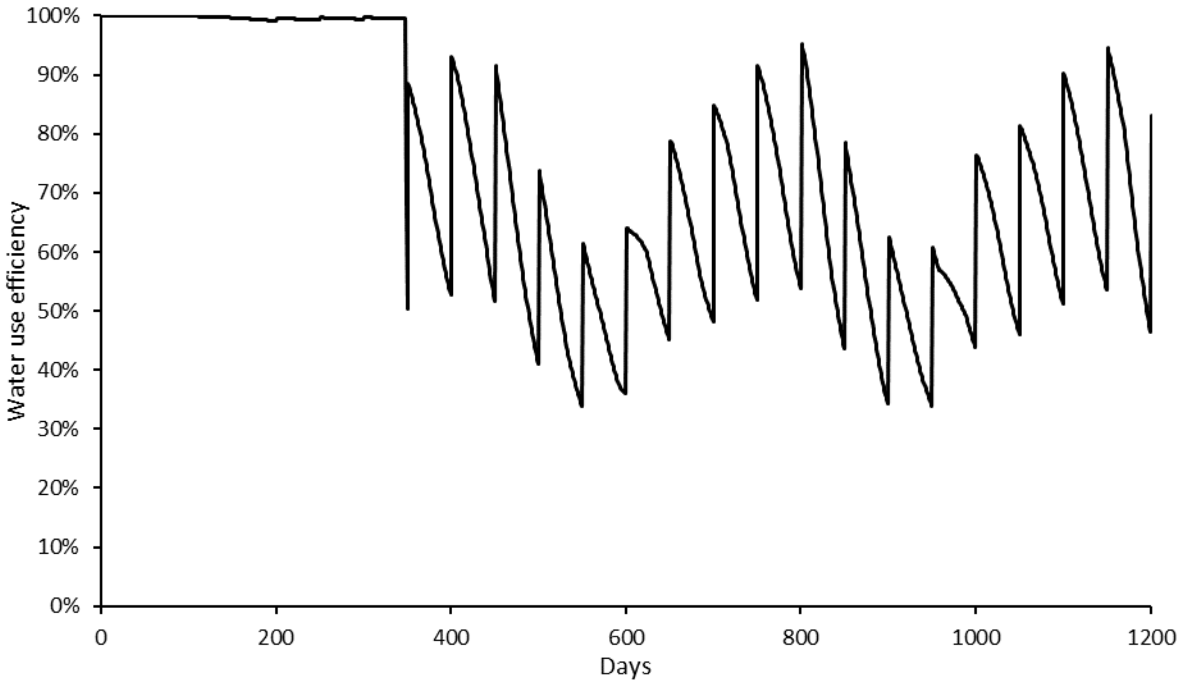

Figure 10 Water use efficiency (WUE) of water in the KeniAP system.

Previously explained principles also explain the WUE behavior from ~day 350 on. The slight variations seen in the first 350 days are explained by water lost in the waste sludge of the anaerobic digester. Water lost in the waste sludge of the anaerobic digester follows the 50-day pattern caused by the amount of feed input, reaching a maximum when feed input is at its’ highest point.

3.2 Uncertainty analysis

The effect of uncertainty in feed composition, digester mineralization rates, climate conditions and solid:soluble excretion ratio on model outputs is investigated.

In Table 9, the effect of varying feed protein content on model output is shown. The uncertain protein content of fish feed does create negligible uncertainty in key performance indicators concerning sustainability, as reflected in the sensitivity values in Table 9. Supplementing of N in the nutrient solution is required when feed protein content is low.

Table 9 Key performance indicator values and other system parameters under varying feed protein content, along with the corresponding sensitivity values.

	Protein content			
Parameter	*30%*	*40%*	*S*	**Unit**
NUE N	65.93	66.27	0.018	%
NUE P	77.00	77.00	0	%
WUE	65.23	65.23	0	%
Feeding rate	9.08	9.08	0	g m^{-2} d^{-1}
N in feed	654	872	1	kg
P in feed	204	204	0	kg
N supplemented	21.62	0.036	-500	kg
P supplemented	0	0	n.a.	kg

In Table 10, the effect of varying phosphorus content on model outputs is shown. Variation in P content has a significant impact on the sustainability of the system, in terms of nutrient and water use. An increase in P content has a negative effect on the NUE N, NUE P, and WUE, this negative effect being the largest on WUE, as can be concluded from the sensitivity values. This observation can be explained by the fact that a high P content in feed results in a high dilution requirement, during which large amounts of both water and nutrients are lost. Notable is that a P content of 1 wt% results in a significantly higher NUE of P and WUE than for the nominal situation (P content 1.5 wt%). The sensitivity values for supplemented N are high for both variation in protein content and P content. This can be explained by the fact that supplemented N is only 0.151 kg in the nominal situation.

Table 10 Key performance indicator values and other system parameters under varying feed phosphorus content, along with the corresponding sensitivity value.

	P content			
Parameter	*1 wt%*	*2 wt%*	*S*	**Unit**
NUE N	75.66	59.47	-0.368	%
NUE P	93.16	67.42	-0.501	%
WUE	96.04	48.02	-1.10	%
Feeding rate	9.08	9.08	0	g m^{-2} d^{-1}
N in feed	763	763	0	kg
P in feed	136	272	1	kg
N supplemented	0.151	64.691	641	kg
P supplemented	0	0	n.a.	kg

Nutrient mobilization rates of the anaerobic digester are uncertain. Uncertainty caused by an uncertain nitrogen mobilization rate is shown in Table 11. Uncertainty of the N mobilization rate has a small impact on the NUE N, as reflected by the sensitivity value. Furthermore, a higher mobilization rate completely removes the need for N supplementing.

Table 11 Key performance indicator values and other system parameters under nitrogen mobilization rates of the anaerobic digester, along with the corresponding sensitivity values.

	N mobilization rate			
Parameter	*10%*	*50%*	*S*	**Unit**
NUE N	62.94	71.68	0.083	%
NUE P	77.00	77.00	0	%
WUE	65.23	65.23	0	%
Feeding rate	9.08	9.08	0	g m^{-2} d^{-1}
N in feed	763	763	0	kg
P in feed	204	204	0	kg
N supplemented	22.739	0	-94118	kg
P supplemented	0	0	n.a.	kg

Uncertainty caused by an uncertain phosphorus mobilization rate is shown in Table 12. At a low P mobilization rate, WUE is high, but NUE of P is low. In this case, the dilution requirement is low because the inflow of P into the nutrient solution from the anaerobic digester is low. However, a lot of P is lost in the waste sludge of the digester. Furthermore, constant supplementing of P into the nutrient solution is necessary to meet the P concentration requirement. The uncertainty caused by an uncertain P mobilization rate is small compared to the uncertainty caused by uncertain feed contents. WUE is the most sensitive to an uncertain P mobilization rate, which can be explained by the fact that high P mobilization rates lead to dilution of the nutrient solution.

Table 12 Key performance indicator values and other system parameters under varying phosphorus mobilization rates of the anaerobic digester, along with the corresponding sensitivity values.

	P mobilization rate			
Parameter	*10%*	*95%*	*S*	**Unit**
NUE N	76.69	65.00	-0.052	%
NUE P	57.62	77.07	0.074	%
WUE	99.54	62.36	-0.168	%
Feeding rate	9.08	9.08	0	g m^{-2} d^{-1}
N in feed	763	763	0	kg
P in feed	204	204	0	kg
N supplemented	0.151	3.960	7712.990	kg
P supplemented	11	0	n.a.	kg

Both variations in feed composition and variation in mobilization rates have no impact on the energy balance of the system, hence there is no mention of the solar collectors and PV panel surface requirement in Table 9, Table 10, Table 11, and Table 12.

Table 13 Key performance indicator values and other system parameters under varying climate conditions.

	Relative humidity		*Temperature*		
Parameter	*High*	*Low*	*High*	*Low*	**Unit**
NUE N	66.31	65.65	66.73	65.26	%
NUE P	77.52	76.50	78.19	75.9	%
WUE	66.24	64.26	67.53	63.09%	%
Feeding rate	9.08	9.08	9.08	9.08	g m^{-2} d^{-1}
Solar collector requirement	6.8	6.6	6.9	6.5	m^2
PV-panel requirement	78.1	78.1	78.1	78.0	m^2
N in feed	763	763	763	763	kg
P in feed	204	204	204	204	kg
N supplemented	0.157	0.144	0.192	0.124	kg
P supplemented	0	0	0	0	kg

Relative humidity and temperature directly affect evapotranspiration rate and thereby have an impact on the system. Uncertainty in climate conditions does not have a significant effect on model outputs. High RH and high temperature result in a higher evapotranspiration rate, which leads to a higher WUE and higher NUE for both N and P. In the low-temperature scenario, evapotranspiration rate is lower, meaning less water has to move from the RAS to the HPS. Therefore, less groundwater needs to flow into the RAS, explaining a lower solar collector requirement. Given that less water moves from the RAS to the HPS, more COD is present in RAS water, meaning more COD will flow to the digester. This higher COD concentration results in slightly higher methane yield, reducing the requirement for solar panels by 0.1 m^2 compared to the nominal situation.

The effect of uncertain solid:soluble excretion ratios of nitrogen and phosphorus on model outputs are respectively shown in Table 14 and Table 15.

Table 14 Key performance indicator values and other system parameters under varying nitrogen metabolism parameters, along with the corresponding sensitivity values. It is indicated whether solid or soluble excretion is favored, compared to the nominal situation, along with the solid:soluble excretion ratio value.

	Nitrogen			
Parameter	*Soluble N (0.211)*	*Solid N (0.643)*	*S*	**Unit**
NUE N	68.00	64.07	-0.054	%
NUE P	77.00	77.00	0	%
WUE	65.23	65.23	0	%
Feeding rate	9.08	9.08	0	g m^{-2} d^{-1}
N in feed	763	763	0	kg
P in feed	204	204	0	kg
N supplemented	0.106	10.232	61800	kg
P supplemented	0	0	n.a.	kg

Table 15 Key performance indicator values and other system parameters under varying phosphorus metabolism parameters, along with the corresponding sensitivity values. It is indicated whether solid or soluble excretion is favored, compared to the nominal situation, along with the solid:soluble excretion ratio.

	Phosphorus			
Parameter	*Soluble P (1.25)*	*Solid P (5.00)*	*S*	**Unit**
NUE N	65.78	66.19	0.004	%
NUE P	77.10	76.89	-0.002	%
WUE	64.70	65.85	0.010	%
Feeding rate	9.08	9.08	0	g m^{-2} d^{-1}
N in feed	763	763	0	kg
P in feed	204	204	0	kg
N supplemented	0.239	0.151	-0.339	kg
P supplemented	0	0	n.a.	kg

Uncertainty in fish metabolism parameters has no impact on the energy balance of the system, hence there is no mention of the solar collector and PV panel surface requirement in Table 14 and Table 15. When soluble excretion of either nutrient is favored, NUE is higher. This observation can be explained by the fact that part of the solid excretion is lost in the waste sludge of the digester. Since the mobilization rate of P in the anaerobic digester is higher, the effect of an uncertain solid:soluble excretion ratio on the NUE of P is lower. When solid excretion of N is favored, supplementing of N is 100 times the amount of when soluble excretion of N is favored. The reason for this is that more solid excretion of N leads to more loss of N in the waste sludge of the anaerobic digester. Less N will flow into the nutrient solution, increasing the requirement for supplementing. When soluble excretion of P is favored, WUE is lower and the amount of N supplement is higher. If soluble excretion of P is favored, the concentration of P in RAS water is higher, and the concentration of P in the effluent is lower, compared to the situation where solid excretion of P is favored. Overall, this leads to slightly more P flowing into the nutrient solution, leading to a higher dilution requirement of the nutrient solution, and thus a higher supplementing requirement of N. Furthermore, the effect of an uncertain solid:soluble excretion ratio of both nitrogen and phosphorus on the model outputs is small compared to the effect of uncertain feed contents, as reflected by the sensitivity values.

3.3 KeniAP optimal system design

The results of an optimization of sizing parameters are presented, in which the size of the planting area and the max stocking density were decision variable. Optimization was performed with and without the presence of an anaerobic digester, the results of which are found in Table 16.

Table 16 Nominal and optimal sizing for the KeniAP system with and without a digester, at either constant planting area or constant max stocking density, and accompanying performance.

System parameter	*Scenario 1*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Nominal*	**Unit**
Digester present	yes	no	yes	no	yes	n.a.
Planting area	1500	1500	2627	668	1500	m^2
Max stocking density	30	60	40	40	40	kg m^{-3}
NUE N	73.04	67.71	77.74	68.84	65.97	%
NUE P	88.24	51.39	95.09	48.44	77.00	%
WUE	86.62	99.32	99.74	91.68	65.23	%
N supplemented	0.602	0.319	10.424	0.296	0.151	kg
P supplemented	0.0	10.35	0.0	1.22	0.000	kg

Average of NUE P and WUE	87.43	75.35	97.42	70.06	71.12	%
Feeding rate	6.85	13.62	5.19	20.39	9.08	kg m^{-2} d^{-1}
Solar collectors	6.7	6.7	11.7	3.0	6.7	m^2
PV-panels	79.0	76.1	78.2	77.6	78.1	m^2

It can be concluded from the performance indicators that a digester increases the sustainability of an aquaponic system. Without a digester, all nutrients present in fish sludge are lost. Since the digester mineralizes P more than N, NUE of P increases more than NUE of N when a digester is present in the system. Supplementing of P is not required when a digester is present, but unavoidable when no digester is present. Reducing the planting area even more than is done in scenario 4 does not reduce the required amount of P supplement. This reduction of the planting area would lower the total amount of evapotranspiration water, thus decreasing the amount of nutrient transfer from the RAS to the HPS. When no digester is present, nutrients in fish sludge are lost, leading to a higher required feeding rate in order to achieve required nutrient concentrations in the nutrient solution. In scenario 2, the amount of P supplement is higher than in all other scenarios. The lack of a digester combined with a planting area of 1500 m^2 leads to a high requirement of P to achieve the threshold for P concentration in the nutrient solution. The max stocking density is set at the upper limit to maximize the amount of P entering the AP system. The required area of PV-panels is dependent on the max stocking density. At higher stocking density, fish feed input and thus the amount of COD flowing to the digester is higher, meaning more biogas is produced. The required area of solar collectors is dependent on the planting area. A larger planting area means that the total volume of evapotranspiration water is higher. This water loss is replenished by groundwater, which has to be heated before flowing into the RAS.

When a system with 1500 m^2 of plant production and no digester is optimized without constraining the max stocking density to be lower than 60 kg m^{-3}, a stocking density of 85 kg m^{-3} is selected. The amount of P supplement is 1.98 kg, the average of NUE P and WUE is 71.23%, and the feeding rate is 19.32 g m^{-2} d^{-1}. These performance indicator values are similar to those of scenario 4.

Optimal sizing parameters are those of scenario 3, since NUE P and WUE are significantly higher than for the nominal situation. Because the planting area is almost twice as big as for the nominal situation, P concentration in the nutrient solution does not reach its' limit, as seen in Figure 16. Therefore, no dilution of the nutrient solution is required, meaning there is no loss of P and water. However, the concentration of N in the nutrient solution is only sufficient during the months that the evapotranspiration rate is high and thus nutrient transfer from the RAS to the HPS is high. During the months with a low evapotranspiration rate, supplementing of N is required, as seen in Figure 15.

4. Discussion

The objective of this research study was to design a model in order to gain insight into the dynamics of the KeniAP system. With this model, an uncertainty analysis was performed, and the KeniAP system was optimized in terms of efficient use of nutrients, water, and energy. In this section, model design, system performance, and the uncertainty analysis will be discussed.

4.1 Model design

In the HPS, only total N is considered, although the ratio NO_3-N:TAN has an impact on plant growth. It is assumed that total N in the HPS is 75% NO_3-N and 25% N-NH_4. It is safe to make this assumption since both nitrate and TAN enter the system, but due to the HPS being well aerated most N will be present in the form of nitrate-nitrogen (Jones, 2004). Several authors claim that a small mass fraction of N in a hydroponic nutrient solution being TAN boosts plant growth (Jones, 2004; Savvas et al., 2006; Sonneveld, 2002).

Setting accurate nutrient concentration ranges is important. For the KeniAP system, P concentration in the nutrient solution is in many cases a determining factor. Since the concentration range is smaller than the concentration range of N, there is a higher chance for a dilution or supplementation requirement. On top of that, P is an exhaustible resource, meaning that efficient use is more desirable than for N. As reported in chapter 2.2.2, different advices for nutrient concentration requirements for a hydroponic nutrient solution are found in literature. These different advices suggest that nutrient concentration requirements are not as strict as they are presented to be in this research study. Furthermore, when nutrient concentrations do not meet their requirements, it does not mean that there is no yield. When setting the nutrient concentration ranges one should know whether the aim is to achieve optimal, or acceptable nutrient concentrations. With optimal nutrient concentrations, plant growth is optimal. With acceptable nutrient concentrations, plant growth will not be optimal, but no nutrient deficiencies will occur either.

Nutrient concentration requirements of the nutrient solution have an impact on the behavior of the AP system, because they can lead to dilution of the nutrient solution or supplementing of the nutrient solution. Dilution of the nutrient solution is undesirable, since water and nutrients are wasted. Supplementing is less undesirable, but undermines the self-sufficiency of the AP system. Adjusting fish and plant production to each other is important. When done correctly, both supplementing and dilution of the nutrient solution can be avoided, or at least kept to a minimum. In the nominal situation, nutrient and water use efficiency is low, because the size of fish and plant production are not well adjusted to each other.

The model was designed based on one specific AP system, in which a digester is present. However, the use of Microsoft Excel^{TM} allows for easy changes to the model. Because most nutrient and water flows are the same for every AP system, the model can be adjusted to different AP system setups. Setting the biogas yield and mineralization rates to 0 would effectively transform the AP system with a digester to an AP system without a digester. Changing fish metabolism and fish growth parameters would effectively transform the system into a system where a different fish species is produced. For example, the model would also apply to an AP system where African catfish and basil are produced, and no digester is present, as long as the corresponding data is available and used.

When a model is designed, it has to be decided which aspects are considered, and which aspects are disregarded. The order in which aspects are considered goes from relevant to less relevant. In this research study, fish growth and evapotranspiration rate are two examples of aspects deemed to be relevant. The addition of solar energy collection is an example of an aspect which was considered less relevant and was added at later stages. Many aspects that would have an impact on model output are not considered in this research study. These omissions might be because no data is available, such as for the groundwater composition and the greenhouse climate conditions. Fish mortality, plant disease, evaporation of water from the fish tanks, variable fish yield, and variable plant production are aspects that were not included because the impact they have on the model is too small to compensate for how much they would complicate the model (Goddek, 2018).

4.2 Aquaponic system design

A planting area size increase of 75% leads to an optimal system design. Dilution of the nutrient solution does not occur in this situation, meaning that nutrients and water are only lost in the waste sludge of the digester. In reality, increasing the total planting area might not be an option, especially when the system is in an urban area. Whether estimated optimal system sizing parameters are optimal is dependent on the certainty of used parameters. Some flexibility in system size might be beneficial to account for uncertain parameters.

The KeniAP system is not self-sufficient when electric energy is produced using only biogas. The total required surface of solar panels (both solar collectors and PV-panels) to produce the remaining amount of required electric energy is low compared to the total plant area. 85 m^2 of solar panels is required to cover the total energy requirement of the system. However, when solar energy is used to power the system, energy production only occurs during part of the day, whereas energy consumption is spread out over the day. If the aim is to design a self-sufficient AP system, using solar energy requires the need for a means of energy storage.

When biogas is combusted in order to produce electric energy, heat is also produced. The efficiency of converting the methane into energy used by an AP system can be increased by using the produced heat for maintaining RAS water temperature. Furthermore, when implementing a digester in an AP system, the lack of predictability of the amount of energy production needs to be considered. Estimations of the produced heat of a generator should be made to find the fraction of water flowing into the RAS that can be heated by the generator. Solar collectors and PV-panels can be used to produce the remaining amount of required energy.

4.3 System performance

For the computation of the key performance indicators and other system characteristics, the first 150 days are taken out of consideration. However, in the presentation of the results, system dynamics during the first 150 days are given attention, to increase the insight into AP system dynamics. Every aquaponic system that utilizes staggered fish production will go through a start-up phase, in which total fish biomass is different from when the system is running at a normal capacity. Including the start-up phase in the calculation of the key performance indicators' values would skew the results.

Yogev *et al*. (2016) suggest that an AP system with a 15 m^3 RAS and 5000 m^2 of plant area would be self-sufficient in terms of energy, using only a digester. Although the KeniAP system is even larger than this, it is not in line with this suggestion. This discrepancy can be explained by the fact that Yogev *et al*. (2016) assume a higher conversion efficiency for biogas energy content, a lower power consumption of AP electronics, a higher feed conversion rate, and use plant biomass waste as feedstock for the digester. These difference in outcomes show how difficult it is to estimate the energy yield of implementing a digester into an AP system.

In the nominal situation, the feeding rate of the system is 9.08 g d^{-1} m^{-2}. Rakocy *et al*. (2004) produced basil and tilapia in an aquaponic system, using a feeding rate of 99.6 g d^{-1} m^2. The used system was a single loop system without a digester. Lennard (2012) suggests a much lower feeding rate of 16 g d^{-1} m^2 for an aquaponic system where tilapia and lettuce are combined. He adds that a higher crop density is possible, leading to an even lower feeding rate ratio. Endut *et al*. (2010) speak of an optimal feeding rate of 15-42 g d^{-1} m^{-2} in an aquaponic system with African catfish (*Clarias gariepinus*) and spinach. Feeding rate in the KeniAP system is much lower, which can be explained by the difference in system design. The KeniAP system has a digester, resulting in nutrient mobilization which makes fish feed more efficient as a nutrient supplier for the plants. One also has to consider that only N and P are regarded in this model; other nutrients required by plants might be in shortage in the current situation. In chapter 3.3 it became apparent that feeding rates would be ~20 g d^{-1} m^{-2} if no digester would be present in the AP system, and supplementing of P is restricted. These feeding rates are corresponding with previously mentioned feeding rates that are observed in literature.

Dilution of the nutrient solution has a large impact on NUE and WUE of the KeniAP system. Pairing a hydroponic system with an aquaculture system means it is more difficult to control nutrient concentrations in the nutrient solution. The inflow of nutrients via fish feed means that the ratio of nutrients present in an AP system is dependent on the ratio of nutrients in fish feed. When nutrients inflow happens solely due to supplementing, this ratio can be controlled by the user, meaning it is easier to meet nutrient concentration requirements. However, the idea of aquaponics is to use the waste of a RAS as input for an HPS. Relying on supplementing of nutrients contradicts this idea.

4.4 Uncertainty analysis

During the uncertainty analysis, it was found that the effect of varying climate conditions has little effect on the performance of the system in terms of environmental sustainability. However, it might have an effect on the performance of the system in terms of yield, because varying climate conditions do have an effect on plant growth. Uncertainty in protein content had a small effect on the performance of the system in terms of sustainability. On the other hand, it might have an effect on fish growth, and thus on fish biomass yield. The focus of this research study was on the environmental sustainability of the AP system, although economic sustainability is also a necessity for the AP system.

NUE P and WUE have a high degree of sensitivity to uncertainty in P content of fish feed, meaning that it is important that the P content of fish feed is accurately known. Underestimation of P content of fish feed can lead to overestimation of the P supplement requirement. As a result, P concentration can become too high, leading to high water and nutrient losses due to dilution of the nutrient solution. Overestimation of P can lead to underestimation of the P supplement requirement, leading to a low P concentration which has a negative impact on plant growth.

Time constrains the number of parameters involved in the uncertainty analysis as well. The selection of parameters that was regarded in the uncertainty analysis was deemed to be most relevant and interesting, based on expert knowledge (Goddek, 2018). Examples of parameters that could have been included in the uncertainty analysis are: nutrient concentration ranges, fraction of uneaten feed, solid:soluble excretion ratio of COD, COD content of fish feed, and methane yield per unit of mass of COD.

5. Conclusions

In the nominal situation, the KeniAP aquaponic system (AP) consists of a 50 m^3 recirculating aquaculture system (RAS), in which Nile tilapia are produced, a 1500 m^2 hydroponic system (HPS), in which tomato and lettuce are produced, and an anaerobic digester. Fish growth determines the fish feed requirement, and thus nutrient input into the AP. Nutrient concentration ranges for the nutrient solution are set to represent the plant nutrient requirement. When the minimum nutrient concentration for the nutrient solution is not achieved, nutrients are supplemented. Furthermore, when the maximum nutrient concentration is surpassed, dilution of the nutrient solution occurs. Fish sludge flows from the RAS to the digester, where it is converted into biogas, mineralized nutrients, and waste sludge. The COD of the fish sludge is used to predict the biogas yield. To gain insight into system dynamics and performance of the KeniAP systems, a model is designed. Mass balance differential equations were created for nitrogen (N), phosphorus (P) and COD. Moreover, water and energy balance differential equations were set up. The solutions of these balance differential equations were approximated in Microsoft Excel™ using the forward Euler method. Fish growth follows a 50-day pattern due to staggered fish production, in which one fish tank is harvested per 50 days. The volume of evapotranspiration water follows a 365-day pattern, due to climate conditions. Therefore, both a 50-day pattern and a 365-day pattern are visible in nutrient concentrations in both the RAS and the HPS. The nutrient concentration ranges have a significant impact on system behavior. Due to the high mineralization rate of P in the digester, P concentration reaches its maximum before N reaches its' maximum. Dilution of the nutrient solution occurs, leading to such a loss of N, that supplementing of N is required.

Nutrient use efficiency (NUE), water use efficiency (WUE), and energy use are key performance indicators of the KeniAP system with regards to environmental sustainability. NUE and WUE indicate the fraction of nutrients and water input that is used for fish and plant production. Furthermore, the feeding rate is a key performance indicator to allow for comparison with aquaponic systems reviewed in literature.

Relevant uncertain model parameters for which an uncertainty analysis was performed are the ratio of solid:soluble excretion by fish, air temperature, relative humidity (RH), fish feed protein and P content, and N and P mineralization rate in the digester.

The model outputs are most sensitive to uncertainty in fish feed P content and P mineralization rate. This effect can be explained by the fact that the P concentration range is small, easily leading to a dilution requirement of the nutrient solution. Uncertain temperature values lead to a small amount of uncertainty in model outputs. Variation in temperature leads to variation of the evapotranspiration rate, thus variation of the nutrient use of the HPS.

In the nominal situation, NUE of N, P, and WUE respectively have values of 65.97%, 77.00%, and 65.23%. 84.8 m^2 of solar panels are required to cover the energy use of the system, and the feeding rate is 9.08 g fish feed per day per m^2 of plant area. An optimization of system sizing parameters was performed to improve the NUE of P and the WUE. The size of the HPS is increased to 2627 m^2. A larger plant area leads to higher nutrient use, which removes the need for dilution of the nutrient solution. NUE N, NUE P, and WUE have values of 77.74%, 95.09%, and 99.74%. 89.9 m^2 of solar panels is sufficient to cover the energy requirement of the system, and the feeding rate is 20.09 g m^{-2} d^{-1}.

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Appendices

Table 17 RAS properties

Property	Value	Unit
Tanks	4	#
RAS size m3	50	m^3
Tank size	12500	L
Tank size m3	12.5	m^3
RAS size L	50000	L
NO3 limit	400	mg/L
NO2 limit	5	mg/L
NH3-N Limit	0.1	mg/L
Biofilter efficiency	95%	% TAN nitrified
Temperature fish tank	29.5	°C
pH	7	
# fish	110	fish m^{-3}

Table 18 Weather data of the nominal situation, compiled from weather data of eight years (2009-2016).

	Max Temperature[1]	**Min Temperature**[1]	**RH_{max}**[1]	**RH_{min}**[1]	**RH**[1]	**Solar Radiation (R_S)**[2]	ET_0
	°C	°C	%	%	%	MJ/m2/day	mm/day
January	26.3	13.0	81.1	61.1	71.1	25.64	2.46
February	27.8	14.1	76.3	56.3	66.3	25.75	2.54
March	27.5	15.0	78.9	58.9	68.9	25.32	2.56
April	25.3	15.9	92.0	72.0	82.0	20.3	2.14
May	23.9	14.8	95.5	75.5	85.5	18.29	1.88
June	23.4	13.9	92.1	72.1	82.1	15.53	1.57
July	23.8	12.9	85.6	65.6	75.6	15.71	1.55
August	24.1	13.9	82.6	62.6	72.6	15.66	1.59
September	26.0	14.8	78.4	58.4	68.4	20.72	2.09
October	26.3	15.6	79.6	59.6	69.6	21.24	2.18
November	24.9	15.1	89.3	69.3	79.3	21.46	2.19
December	25.0	13.6	89.4	69.4	79.4	24.78	2.42

[1] Derived from worldweatheronline.com
[2] (Onyango and Ongoma, 2015)

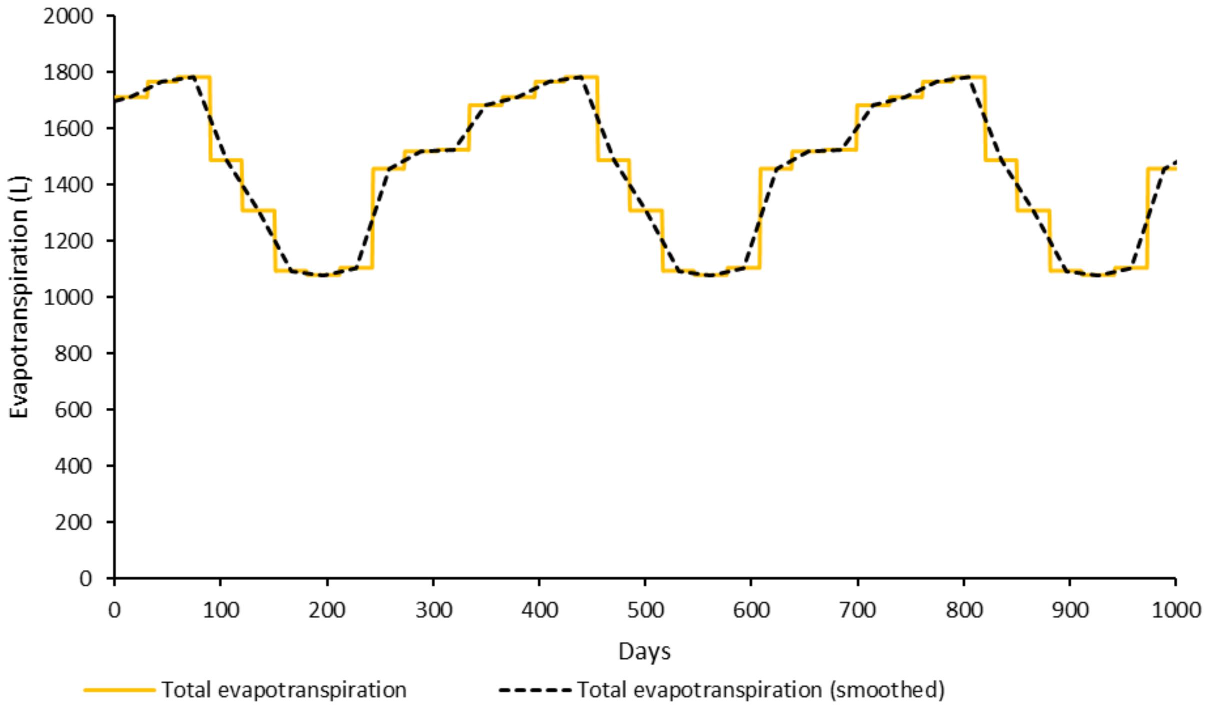

Figure 11 Evapotranspiration in the primary situation of the KeniAP system, in which day 0 is January 1st.

Table 19 Order in which calculation steps are taken to numerically solve the water balance differential equations.

Calculation step	Symbol	Equation	Unit
Fish sludge water	Q^{SW}	Eq. 7	L
Effluent of anaerobic digester	Q^{ANA}	Eq. 14	L
Water in waste sludge of anaerobic digester	n.a.	n.a.	L
RAS water removal due to dilution	V_{dl}^{RAS}	Eq. 11	L
Shortage/surplus of water in HPS due to evapotranspiration, effluent water, and RAS dilution water.	n.a.	n.a.	L
HPS water removal due to dilution	V_{dl}^{HPS}	Eq. 8	L
Total water in waste streams	n.a.	n.a.	L
Total water input	n.a.	n.a.	L

Table 20 Order in which calculation steps are taken to numerically solve the mass balance differential equations of N, NO_3-N, and TAN.

Calculation step	Symbol	Equation	Unit
N in eaten feed	n.a.	n.a.	mg
Fish retention of N	n.a.	n.a.	mg
N in uneaten feed	n.a.	n.a.	mg
N in feces	n.a.	n.a.	mg
N in solids in the fish tanks	n.a.	n.a.	mg
TAN excretion by fish	p^{TAN}	Eq. 16	mg
NO_3-N in RAS	$m_{RAS}^{NO_3-N}$	n.a.	mg
TAN in RAS	m_{RAS}^{TAN}	n.a.	mg

NO_3-N in RAS after fish sludge water removal and subsequent refilling with groundwater	$m_{RAS}^{NO_3-N}$	n.a.	mg
TAN in RAS after fish sludge water removal and subsequent refilling with groundwater	m_{RAS}^{TAN}	n.a.	mg
N in the effluent of anaerobic digester	n.a.	n.a.	mg
N in waste sludge of anaerobic digester	n.a.	n.a.	mg
N in HPS after the inflow of effluent of the anaerobic digester	m_{HPS}^{N}	n.a.	mg
N-NH_3 in RAS	n.a.	n.a.	mg L^{-1}
Dilution requirement in RAS with regards to N-NH_3 and NO_3-N	n.a.	n.a.	L
NO_3-N in RAS after dilution of RAS water	$m_{RAS}^{NO_3-N}$	n.a.	mg
TAN in RAS after dilution of RAS water	m_{RAS}^{TAN}	n.a.	mg
N-NH_3 in RAS after dilution of RAS water	n.a.	n.a.	mg
N in HPS after dilution of RAS water	m_{HPS}^{N}	n.a.	mg
N in HPS after removal of N due to evapotranspiration	m_{HPS}^{N}	n.a.	mg
N in HPS after either removing surplus water or adding RAS water to refill	m_{HPS}^{N}	n.a.	mg
NO_3-N in RAS after HPS refill and subsequent refilling of RAS with groundwater	$m_{RAS}^{NO_3-N}$	n.a.	mg
TAN in RAS after HPS refill and subsequent refilling of RAS with groundwater	m_{RAS}^{TAN}	n.a.	mg
Dilution requirement in HPS with regards to N	n.a.	n.a.	L
N in HPS after dilution and adding groundwater to refill	m_{HPS}^{N}	n.a.	mg
N removal from the HPS due to dilution	n.a.	n.a.	mg
Required amount of N supplement	$\dot{m}_{supp}^{N}$	Eq. 20	mg
N in HPS after supplement	m_{HPS}^{N}	n.a.	mg
N in HPS	m_{HPS}^{N}	n.a.	mg L^{-1}
NO_3-N in RAS	$m_{RAS}^{NO_3-N}$	n.a.	mg L^{-1}
TAN in RAS	m_{RAS}^{TAN}	n.a.	mg L^{-1}

Table 21 Order in which calculation steps are taken to numerically solve the mass balance differential equations of P.

Calculation step	**Symbol**	**Equation**	**Unit**
P in eaten feed	n.a.	n.a.	mg
P in uneaten feed	n.a.	n.a.	mg
P retained by fish	n.a.	n.a.	mg
P in feces	n.a.	n.a.	mg
Soluble excretion of P	n.a.	n.a.	mg
P in solids in the fish tanks	n.a.	n.a.	mg
P in RAS	m_{RAS}^{P}	n.a.	mg
P in RAS after fish sludge water removal and subsequent refilling with groundwater	m_{RAS}^{P}	n.a.	mg
P in the effluent of the anaerobic digester	n.a.	n.a.	mg
P in waste sludge of anaerobic digester	n.a.	n.a.	mg
P in HPS after the inflow of effluent of the anaerobic digester	m_{HPS}^{P}	n.a.	mg

P in RAS after dilution of RAS water and subsequent refilling with groundwater	m_{RAS}^{P}	n.a.	mg
P in HPS after dilution of RAS water	m_{HPS}^{P}	n.a.	mg
P in HPS after removal of P due to evapotranspiration	m_{HPS}^{P}	n.a.	mg
P in HPS after either removing surplus water or adding RAS water to refill	m_{HPS}^{P}	n.a.	mg
P in RAS after HPS refill and subsequent refilling of RAS with groundwater	m_{RAS}^{P}	n.a.	mg
Dilution requirement in HPS with regards to P	n.a.	n.a.	L
P in HPS after dilution and subsequent refilling of HPS with groundwater	m_{HPS}^{P}	n.a.	mg
P removal from HPS due to dilution	n.a.	n.a.	mg
Required amount of P supplement	$\dot{m}_{supp}^{P}$	Eq. 20	mg
P in HPS after supplement	m_{HPS}^{P}	n.a.	mg
P in HPS	m_{HPS}^{P}	n.a.	mg L^{-1}
P in RAS	m_{RAS}^{P}	n.a.	mg L^{-1}

Table 22 Order in which calculation steps are taken to numerically solve the mass balance differential equation of COD and yield of methane.

Calculation step	**Symbol**	**Equation**	**Unit**
COD of eaten feed	n.a.	n.a.	kg
COD of uneaten feed	n.a.	n.a.	kg
COD of feces	n.a.	n.a.	kg
COD of solids in the fish tanks	n.a.	n.a.	kg
COD of soluble excretion	n.a.	n.a.	kg
COD in RAS	m_{RAS}^{COD}	n.a.	kg
COD in RAS after fish sludge water removal and refilling with groundwater	m_{RAS}^{COD}	n.a.	kg
COD to digester	$\dot{m}_{dig}^{COD}$	Eq. 24	kg
COD in RAS after dilution of RAS water and subsequent refilling with groundwater	m_{RAS}^{COD}	n.a.	kg
COD in RAS after HPS refill and subsequent refilling of RAS with groundwater	m_{RAS}^{COD}	n.a.	kg
Methane yield	n.a.	n.a.	m^3

Table 23 Order in which calculation steps are taken to numerically solve the energy balance differential equation.

Calculation step	**Symbol**	**Equation**	**Unit**
Energy production by the generator	p_{gen}^{E}	Eq. 27	kWh
Energy requirement of heating inflowing groundwater in RAS	Q_{gw}^{E}	Eq. 30	kWh
Energy use of electronics in AP system	n.a.	n.a.	kWh
Total energy use of the system	n.a.	n.a.	kWh
Net energy yield	n.a.	n.a.	kWh

Table 24 Weather data for all scenarios of the uncertainty analysis. Note that max and min temperature are averages of the daily max and min temperature of an entire month.

Scenario with high RH					
	Max Temperature	**Min Temperature**	RH_{max}	RH_{min}	RH
	°C	°C	%	%	%
January	26.3	13.0	90	70	80
February	27.8	14.1	90	70	80
March	27.5	15.0	95	75	85
April	25.3	15.9	98	78	88
May	23.9	14.8	99	79	89
June	23.4	13.9	95	75	85
July	23.8	12.9	91	71	81
August	24.1	13.9	88	68	78
September	26.0	14.8	83	63	73
October	26.3	15.6	87	67	77
November	24.9	15.1	93	73	83
December	25.0	13.6	95	75	85

Scenario with low RH					
	Max Temperature	**Min Temperature**	RH_{max}	RH_{min}	RH
	°C	°C	%	%	%
January	26.3	13.0	70	50	60
February	27.8	14.1	69	49	59
March	27.5	15.0	67	47	57
April	25.3	15.9	88	68	78
May	23.9	14.8	92	72	82
June	23.4	13.9	86	66	76
July	23.8	12.9	79	59	69
August	24.1	13.9	75	55	65
September	26.0	14.8	72	52	62
October	26.3	15.6	73	53	63
November	24.9	15.1	87	67	77
December	25.0	13.6	86	66	76

Scenario with high temperatures					
	Max Temperature	**Min Temperature**	RH_{max}	RH_{min}	RH
	°C	°C	%	%	%
January	29.0	15.0	81	61	71
February	30.0	15.0	76	56	66
March	30.0	16.0	79	59	69
April	27.0	18.0	92	72	82
May	26.0	17.0	96	76	86
June	26.0	15.0	92	72	82

July	27.0	14.0	86	66	76
August	27.0	15.0	83	63	73
September	28.0	15.0	78	58	68
October	29.0	16.0	80	60	70
November	26.0	16.0	89	69	79
December	27.0	15.0	89	69	79

Scenario with low temperatures					
	Max Temperature	**Min Temperature**	RH_{max}	RH_{min}	RH
	°C	°C	%	%	%
January	23.0	12.0	81	61	71
February	25.0	13.0	76	56	66
March	24.0	14.0	79	59	69
April	24.0	14.0	92	72	82
May	22.0	14.0	96	76	86
June	22.0	12.0	92	72	82
July	22.0	12.0	86	66	76
August	22.0	13.0	83	63	73
September	24.0	14.0	78	58	68
October	23.0	15.0	80	60	70
November	23.0	15.0	89	69	79
December	23.0	13.0	89	69	79

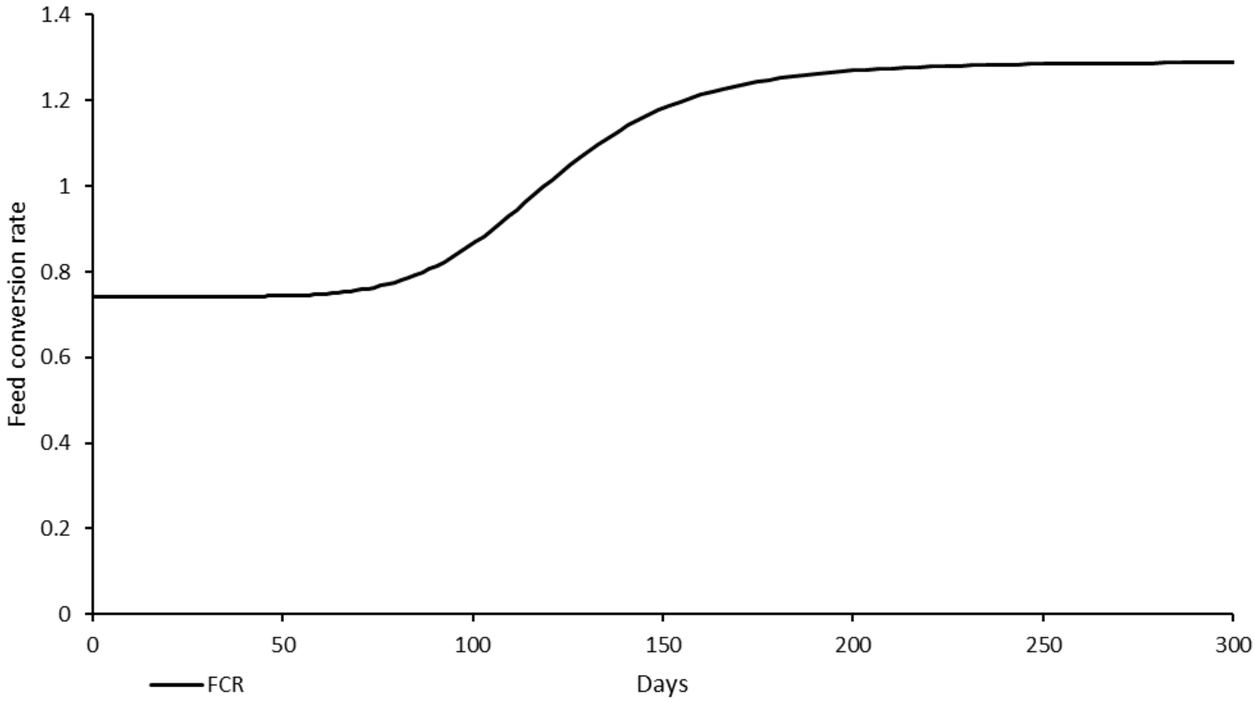

Figure 12 Feed conversion ratio curve for tilapia (kg feed per kg growth).

Table 25 KeniAP-specific parameters used in computation of evapotranspiration using the FAO Penman-Monteith equation.

Parameter	**Value**	**Unit**
Wind speed	0.018	m s^{-1}
Greenhouse glazing transmittance	75	%
Shading factor	25	%
Canopy reflection coefficient	0.23	-
Altitude	1800	m
Latitude	-1	°
Minutes	47	‘

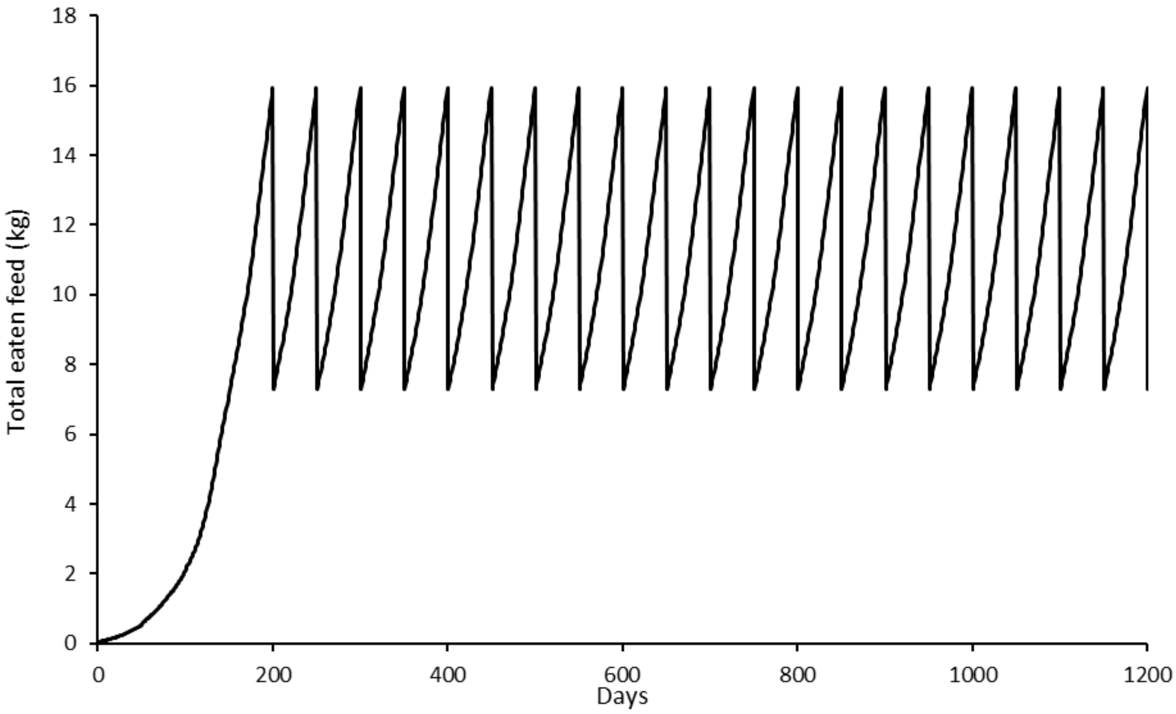

Figure 13 Mass of feed eaten by Nile tilapia in the RAS.

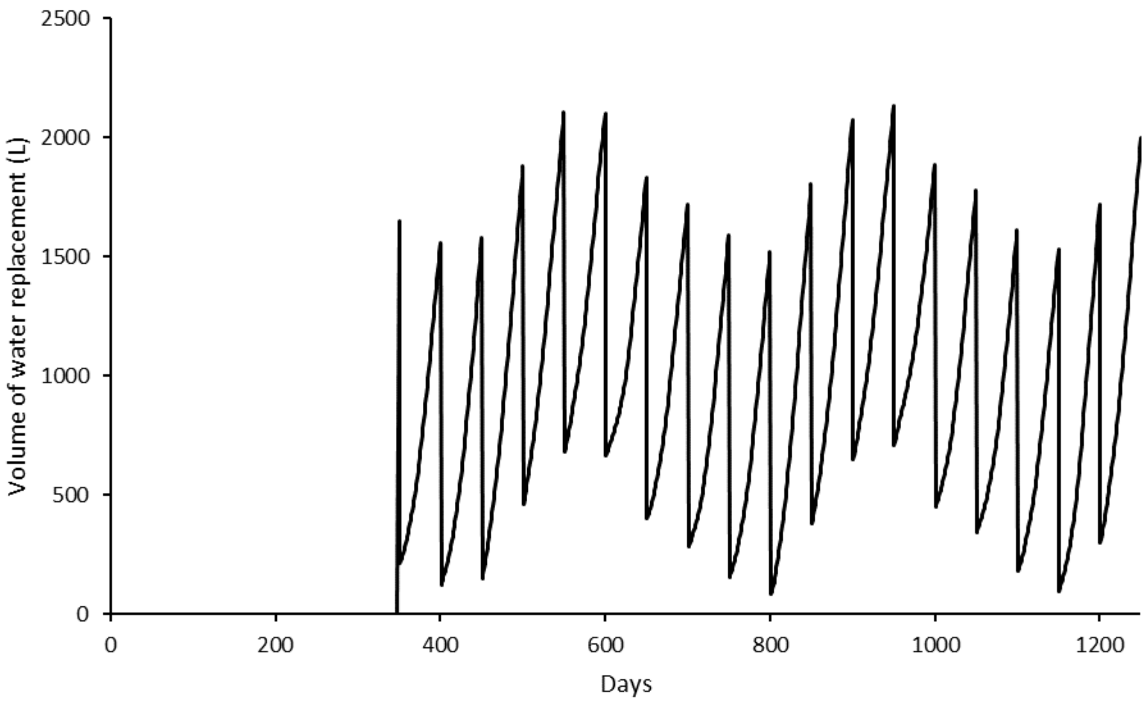

Figure 14 Required volume of water replacement of the nutrient solution.

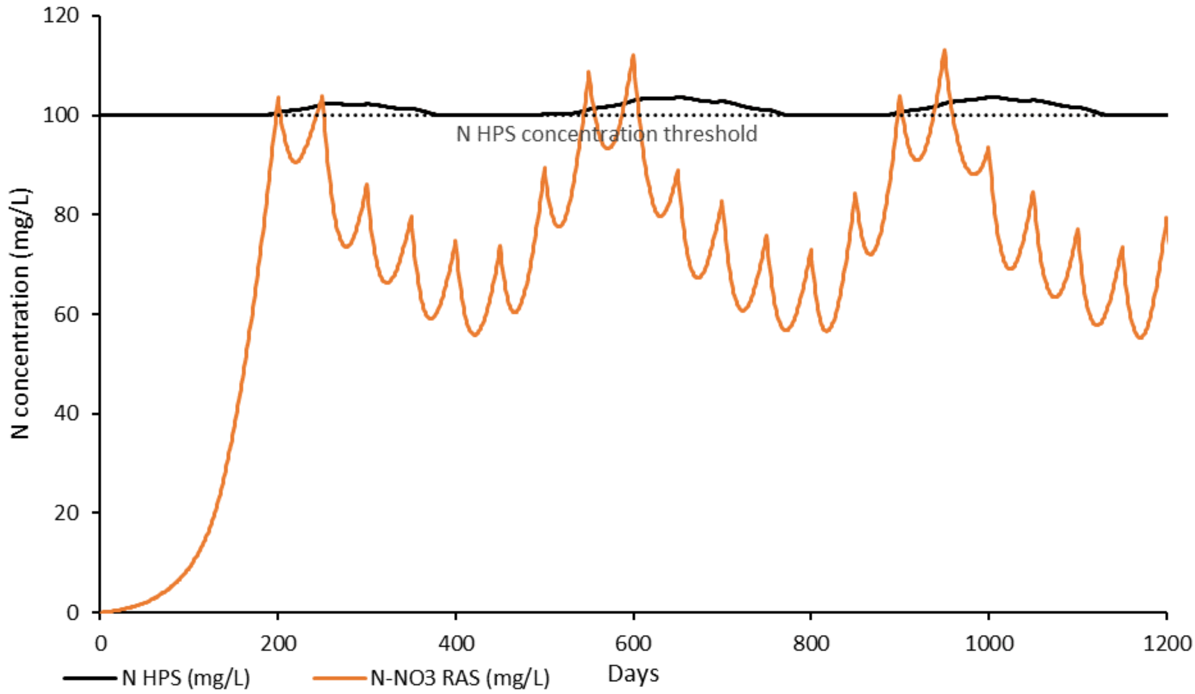

Figure 15 Nitrogen concentration in the nutrient solution, along with the concentration threshold, and nitrate-nitrogen concentration in RAS water, for the system with optimal sizing parameters.

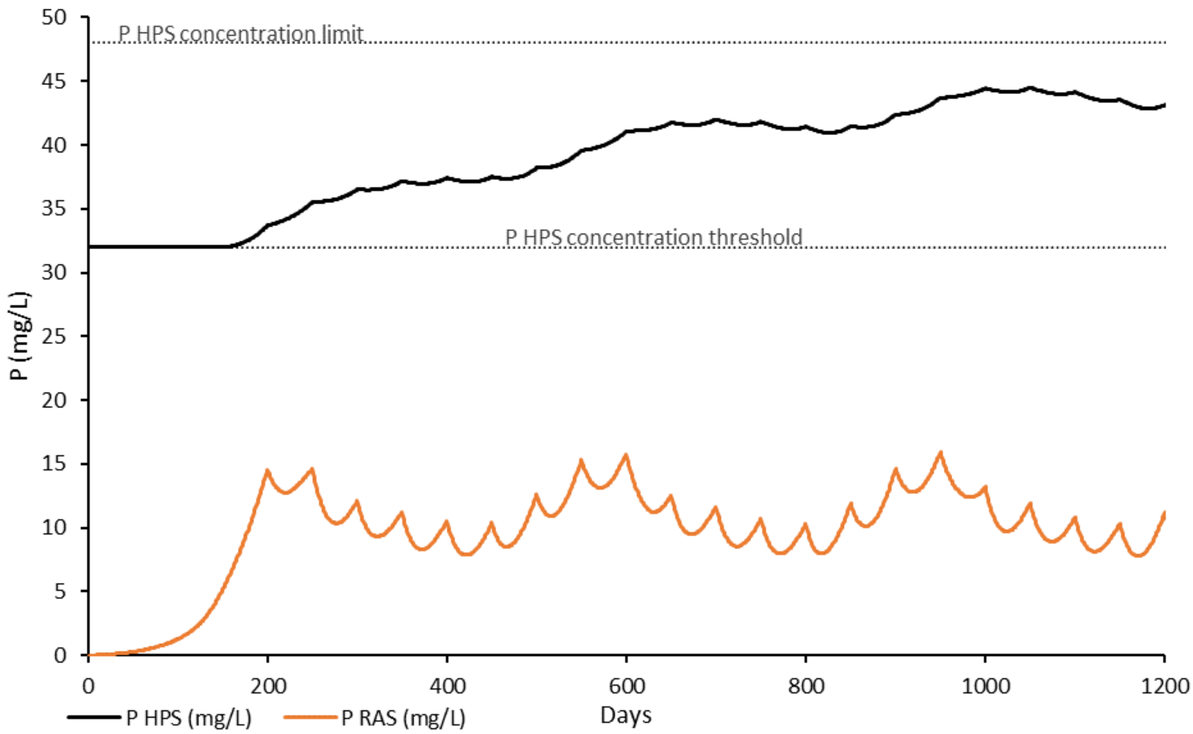

Figure 16 Phosphorus concentration in the nutrient solution, along with the concentration limit and threshold, for the system with optimal sizing parameters.