Significant factors affecting the economic sustainability of closed aquaponic systems.
Part I: system design, chemo-physical parameters and general aspects

Harry W. Palm, Robert Seidemann, Sebastian Wehofsky, Ulrich Knaus

University of Rostock, Faculty of Agricultural and Environmental Sciences, Aquaculture and Sea-Ranching, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany.
Corresponding author: H. W. Palm, harry.palm@uni-rostock.de

Abstract. Two identical closed ebb-flow substrate aquaponic systems for warm-water fish were tested for their chemo-physical characteristics under the production of fish and plants in a freshwater environment with an experimental increasing feed input. Each system contained 3.7 m^3 water, and the relationship of the water volume in the aquaculture tank to the settling basin (sedimenter), the biofilter and the hydroponic units was 2.25:1:0.075:0.6 (fish tank:hydroponic unit = 3.75), with a daily water input of 5.77% (±0.20) and a water removal rate of 1.37% (±0.04) per day. The experiment was divided into three sub-experiments (49 days SE I, 56 days SE II, 55 days SE III), characterized by increasing mean (24.85 g (±0.36)) and total (1,217.50 g (±17.68)) feed input levels in SE I, 131.12 g ($\pm$ 4.99) and 7,342.50 g (±279.31) in SE II, and 221.72 g (±8.78) and 11,751.00 g (±465.28) in SE III, respectively. Sub-experiment I was the run-in phase, characterized by low nutrient loads, fish and plant weights. This phase showed increasing values of oxygen, phosphate, salinity and conductivity. SE II was the exponential phase, with increasing feed input, fish and plant weights, until a distinct drop in oxygen levels occurred, and increasing conductivity, salinity and nutrient loads. SE III was the steady phase, where the feed input of 200 g day^{-1} balanced the oxygen level, salinity, conductivity and nutrient load, with a water input of 6.53% (±0.02) and a lower removal rate of 1.23% (±0.00) per day. Nile tilapia fry (*Oreochromis niloticus*) of 0.50 g initial weight resulted in an individual fish weight gain of 60.93 g (±28.95), a specific growth ratio (SGR) of 3.04% d^{-1} (±0.34), 24.25 kg of biomass weight gain and a feed conversion ratio (FCR) of 0.83 in system I, and a non-significant weight gain (p < 0.05) of 51.29 g (±16.20), an SGR of 2.98% d^{-1} (±0.21), 20.42 kg of biomass weight gain and an FCR of 0.93 in system II. The overall yield of tomato biomass was 20.03 kg. In this communication, we describe our experimental ebb-flow aquaponic system to demonstrate the influence of system design on the chemo-physical parameters, system stability, and fish and plant growth. The importance of other, as yet untested, parameters that may influence economic sustainability, e.g. feed design, fish welfare, parasite and pathogen control, fish physiology, fish/plant combinations and product quality, are discussed.
Key Words: aquaponics, ebb- and flow system, physical parameters, system design, *Tilapia*.

Zusammenfassung. Zwei identische Ebbe-und Flutaquaponiksysteme wurden hinsichtlich der Fisch und Pflanzenproduktion sowie der Charakteristika physikalisch-chemischer Wasserparameter verglichen. Die Aquaponiksysteme wurden im geschlossenen Süßwasserkreislauf betrieben. Die Hydroponikeinheit des Aquaponiksystems bestand aus Kiessubstrat. Jedes System besaß ein Wasservolumen von 3,7 m³, mit einem Verhältnis des Wasservolumens im Aquakulturbehälter zum Sedimenter, dem Biofilter und der Hydroponikeinheit von 2,25:1:0,075:0,6 (Fischbehälter : Hydroponik Einheit = 3,75), mit einer täglichen Wasserzugabe von 5,77% ($\pm0,20$) und einer täglichen Wasserentnahme von 1,37% ($\pm0,04$). Das Experiment wurde zeitlich in drei Unterexperimente (UE) geteilt (49 Tage UE I, 56 Tage UE II, 55 Tage UE III), charakterisiert durch steigende Futtermengen im Mittel von 24,85 g ($\pm0,36$ g) und einer Gesamtmenge von 1.217,50 g ($\pm17,68$) in UE I, 131,12 g ($\pm4,99$) im Mittel und Gesamtmenge von 7.342,50 g ($\pm279,31$) in UE II und 221,72 g ($\pm8,78$) im Mittel und einer Gesamtmenge von 11.751,00 g ($\pm465,28$) in UE III. Unterexperiment I war die Einlaufphase des Systems, gekennzeichnet durch geringe Nährstofffrachten sowie Fisch und Pflanzenbiomassen. In dieser Phase stiegen die Werte von Sauerstoff, Phosphat, Salinität und Leitfähigkeit. UE II war die exponentielle Phase mit einer Erhöhung der Futtermittelquantität, Fisch und Pflanzenmassen bis zu einem merklichen Abfall des Sauerstoffgehaltes sowie erhöhten Werten der Salinität, Leitfähigkeit und dem Nährstoffgehalt. UE III war die stationäre Phase mit einem ausgeglichenen Verhältnis von Sauerstoff, Salinität, Leitfähigkeit und dem Nährstoffgehalt aufgrund der stabilen Futtermittelzugabe von 200 g Tag^{-1} sowie einer mittleren Wasserzugabe von 6,53% ($\pm0,02$) und einer geringeren Wasserentnahmerate von 1,23% ($\pm0,00$) pro Tag. Nil Tilapia Larven (*Oreochromis niloticus*) von 0,50 g Initialgewicht zeigten einen individuellen

Zuwachs von 60,93 g (±28,95), eine spezifische Wachstumsrate (SWR) von 3,04% Tag^{-1} (±0,34), 24,25 kg an Biomassezuwachs und einen Futterquotienten (FQ) von 0,83 in System I sowie einen nicht signifikanten Zuwachs (p < 0,05) von 51,29 g (±16,20), SWR von 2,98% Tag^{-1} (±0,21), einen Biomassezuwachs von 20,42 kg und einen FQ von 0,93 in System II. Der Gesamtertrag an Tomaten belief sich auf 20,03 kg. Diese Arbeit beschreibt unser experimentelles Ebbe-und Flutaquaponiksystem mit dem Einfluss des Systemaufbaus auf physikalische und chemische Parameter, der Systemstabilität und dem Wachstum von Fisch und Pflanze. Die Bedeutung bisher nicht untersuchter Parameter, welche die ökonomische Nachhaltigkeit beeinflussen können (Futtermittelzusammensetzung, Fischgesundheit, Kontrolle von Pathogenen und Parasiten, Fisch-Physiologie, Fisch- und Pflanzen-Kombinationen, Produktqualität), werden diskutiert.
Schlüsselworte: Aquaponik, Ebbe- und Flut System, physikalische Parameter, Systemaufbau, *Tilapia*.

Introduction. Aquaponics is the combination of aquaculture (rearing aquatic animals) and hydroponics (the soilless cultivation of plants), benefiting the economic yield and reducing the ecological costs of such systems during the entire production process. The combination of fish and plant cultivation is old in historical terms, going back to the fish and rice cultivation in tropical Asia, India and China of about 2000 years ago, in which the integration of fish with rice plant cultivation was the precursor to finfish culture (Fernando 1993). Other applications include the use of plant units for wastewater treatment (Kivaisi 2001; Vymazal & Kröpfelová 2009) and modern aquaponics, with definite nutrient input levels and a variety of fish-plant-substrate combinations. They all have in common the fact that the processed water from the aquaculture system benefits the attached plant production units, as seen in modern aquaponic analyses (Rakocy 1989; Lennard & Leonard 2004, 2006; Savidov et al 2005; Graber & Junge 2009; Knaus 2012).

The nutrient solution from the fish can reach the plant roots in various different ways. Aquaponic systems often utilize different substrates for growing plants, such as gravel, expanded clay and sand (substrate systems). The plant-growing material (aggregate) is either constantly supplied with the nutrient solution (aggregate systems), or is periodically surrounded by nutrient-enriched water that runs off after a determined time (ebb and flow systems). The nutrient flow to the roots can be assured by: a) using rafts for growing the plants in a recirculating nutrient solution (the floating raft system), b) bathing the plant roots in a constant supply of the nutrient solution, known as the nutrient film technique (NFT, in a closed system), and c) dispersing the nutrient solution directly onto the plant roots via spraying (aeroponics). A special form of a nearly emission-free NFT aquaponic system combines a closed aquaculture unit through a one-way valve with a recirculating hydroponic unit (Kloas et al 2011).

In addition to a variety of different, often experimental aquaponic systems, some facilities have been successfully tested at the commercial scale. Holliman et al (2008) described an aggregate system with cotton gin compost as a substrate, producing tilapia (*Oreochromis* sp.), channel catfish (*Ictalurus punctatus*) and tomato (*Solanum lycopersicum*). The system was built as an indoor integrated aquaponic system, with an overall size of 4 ha. The annual production was 12.5 t for tilapia, 20 t for catfish and 15 t for tomato. The cost effectiveness depended on market prices for the cultivated species. With a market price of 1.80 $ lbs^{-1} for tilapia and 1.50 $ lbs^{-1} for tomato, the annual benefit was 4,222 US$. A more optimistic calculation revealed a profit of 35,050 US$, with the production of 15 t tilapia (1.95 $) and 18 t tomato (1.65 $). Similarly, Rakocy et al (2004) demonstrated the cost effectiveness of a floating raft aquaponic system in the Virgin Islands with tilapia, basil (*Ocimum basilicum*) and okra (*Abelmoschus esculentus*), reaching a benefit of 117,700 US$ of basil per year at batch production (110,210 US$ staggered production) with a 214 m² cultivation area. The batch production of basil showed nutritional deficiency disorders in the basil, in contrast to staggered production. The aquaponic production of okra showed rapid growth, but was not nearly as lucrative as culinary herbs, such as basil. The gross income from okra was expected to be 6,296 US$ per system and year, about 17- to 18-fold less than basil.

Bailey et al (1997) showed viable investments in tilapia and lettuce production. The financial analysis was based on an aquaponic model system with 6, 12 and 24 units optimized for farm operations in the background of the Rakocy-UVI-system. Although

tilapia production occurred in all units without a positive yield, the hydroponic lettuce production covered all variable and fixed costs. The break-even price for total costs was from 11.14-12.40 US$, below the sale price of 20.00 US$ per lettuce case. All system units showed positive returns to risk; however, the larger farm units (12, 24) had more acceptable returns. To demonstrate the benefits of a combined fish and plant cultivation, Savidov (2005) compared the effects of aquaponic and hydroponic cultivation on plants (echinacea - *Echinacea angustifolia*, rosemary - *Rosmarinus officinalis*, lettuce - *Lactuca* sp. variation (var.) Redoak, Atlantis, Concord, basil - *O. basilicum* var. Genovese, tomato - *S. lycopersicum* var. Clarence and cucumber - *Cucumis sativus* var. Alamir)) in a model system with the same quantities of micro- and macronutrients. The aquaponic solution originated from a pre-commercial aquaponic facility with significant levels of organic soluble material. In the beginning, the plants in the aquaponic system had a better relative growth performance compared with those provided with a hydroponic nutrient solution. The author suggested a faster depletion of mineral components and a better uptake of nutrients under aquaponic conditions. Kotzen & Appelbaum (2010) demonstrated the advantages of aquaponic cultivations under desert conditions in Israel, and Kloas et al (2011) developed their system under the premises of highest water efficiency and a nearly emission-free operation in comparison to low-tech closed aquaponic systems.

Considering the difficulties of comparing any of the so-far tested aquaponic systems and the high number of possible system-fish-plant combinations, limited studies have dealt with the underlying processes that determine the success or failure of fish and plant production under constantly changing economic environments. Investigations into low-tech ebb and flow aquaponic systems are scarce. We have studied a closed ebb and flow substrate aquaponic system, identifying the optimal feed input levels and growth performance of Nile tilapia (*Oreochromis niloticus*). Part I of our studies describes the effects of system design and chemo-physical parameters on the system stability. The consequences of the observed differences for the development and sustainable operation of closed aquaponic systems, focusing on the underlying biological processes, are discussed.

Material and Method

Experimental design and data collection*.* The tested facility is characterised as a closed freshwater ebb-flow substrate aquaponic system, combining warm-water fish with a plant cultivation unit. It consisted of two identical aquaponic subsystems, built in a temperate glasshouse on an appr. 50.00 m² surface area (Figure 1).
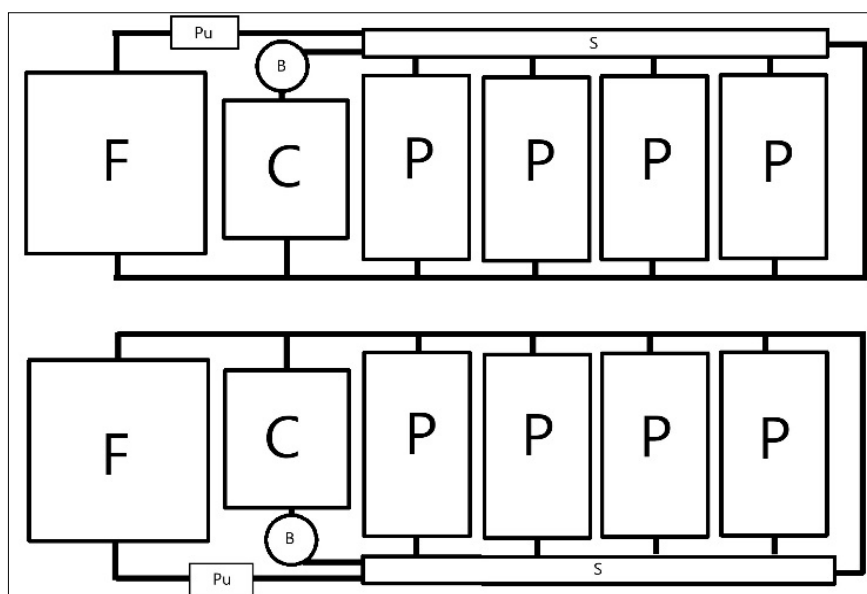

Figure 1. Aquaponic facility at the University of Rostock. Two identical systems with F = fish tank, C = clarifier, P = plant boxes, S = sump, B = biofilter and Pu = Pump.

The water volume was 3.7 m³ in each recirculation system, consisting of a single glass fibre fish tank (3.90 m³, 2.05 x 2.05 x 0.93 m, AquaLogistik, Möhnesee-Wippringsen, Germany) filled with appr. 1,800 L, a clarifier (1.00 m³, IBC) filled with nearly 800 L, four plant boxes (4 x 2.00 m²), a sump (0.61 m³), a trickling filter (200 L) filled with Biocarrier KNS (60 L) and a single pump (UP 40, 3.000 L h^{-1}, AquaLogistik, Möhnesee-Wippringsen, Germany) with a flow-type heater (3.00 KW) automatic control. The hydroponic area was equipped with light rows (RZB Light Stream Flat-Type Maxi, Osram Powerstar HQI-T 400 WIN, Germany) for illumination at night. The plant boxes (2.00 x 2.00 x 0.30 m) were laid out with polyethylene foil (3 mm) and filled with gravel (0.4 m², 2,000 kg) as a substrate, with a maximum water level of 20 cm (120.00 L). The plant boxes were equipped with a water siphon (bell pipe) that allowed one maximum water level within one hour (ebb and flow system, 24 times per day). The amount of water filtered through the plant boxes was set for 11,520 L per day, passing through the hydroponic unit 3.1 times in 24 hours. The relationship of the water volume in the aquaculture unit (1,800 L), the sedimenter (800 L), the biofilter (60 L volume biocarrier), and the hydroponic unit (480 L) was 2.25:1:0.075:0.6 (fish tank:hydroponic unit = 3.75).

The experiment was carried out from the 21.03.2012 to 27.08.2012; the same fish biomass of 199.00 g *O. niloticus* was used in each subunit, with the plant species varying throughout the experimental cycle. The total experimental time (Table 1) was 160 days, separated into three sub-experiments (SE I, SE II, SE III), of 49 days (SE I), 56 days (SE II) and 55 days (SE III). The fish feed input changed throughout the sub-experiments, according to fish growth and system performance, with 24.85 g (±0.36) in mean and 1,217.50 g (±17.68) in total in SE I, 131.12 g (±4.99) and 7,342.50 g (±279.31) in SE II and 221.72 g (±8.78) and 11,751.00 g (±465.28) in SE III.

Table 1

Overview of experiment duration in different sub-experiments

Recirculation unit	Experiment duration (days)	
	Cycle I	Cycle II
Experiment total	160	160
Sub-experiment I (SE I)	49	49
Sub-experiment II (SE II)	56	56
Sub-experiment III (SE III)	55	55

The chemo-physical water parameters of temperature [°C], oxygen [mg L^{-1}], oxygen saturation [%], salinity [‰], conductivity [µs cm^{-1}], pH and redox potential [mv] were taken twice a week using an HQ40D multimeter (Hach Lange GmbH, Germany). Additionally, the nutrient parameters TAN-N [mg L^{-1}], NH$_3$-N [mg L^{-1}], NO$_2$-N [mg L^{-1}], NO$_3$-N [mg L^{-1}] and phosphorus [mg L^{-1}] were measured using the spectral photometer DR-3900 (Hach Lange GmbH, Germany).

Fish and plant species. Each of the aquaponic subsystems (cycle I, II) was stocked with 398 postlarvae *O. niloticus* of 0.50 g, obtained from the University of Wageningen (Netherlands), mixed sex, with a stocking rate of 159 fish m^{-3}. The fish were fed with E-2P Stella (Skretting), 47% crude protein, 14% crude lipid, 2.60% crude fibre and 6.50% crude ash, one time daily by hand. During SE I, the total DFR I (daily feed ratio to biomass, mean) in cycle I was 4% and 25.10 g (±16.20), and the DFR I in cycle II was 4% and 24.59 g (±14.84). During SE II, the total DFR II in cycle I was 5% and 134.64 g (±41.72), and the DFR II in cycle II was 5% and 127.59 g (±47.32). In SE III, the total DFR III in cycle I was 2.5% and 227.92 g (±76.37), and the DFR III in cycle II was 2.5% and 215.51 g (±54.78). The Total Feed Requirement (TFR, mean) of cycle I and II was 131.96 g d^{-1} (±96.42) and 125.14 g d^{-1} (±88.09), respectively.

The plant seeds originated from N. L. Chrestensen Erfurter Samen- und Pflanzenzucht GmbH (Erfurt, Germany). They were seeded in rockwool cubes and

germinal cups until the fourth seed leaf stage, and then they were planted, simultaneously, into the hydroponic plant boxes, at a minimum distance of 0.25-0.30 m. Cycle I was planted with 60 tomato type Moneymaker, 11 butterhead lettuce (*Lactuca sativa*) type Mona, 11 lettuce type Lollo rosso, and 11 spinach (*Spinacia oleracea*) type Matador. In cycle II, 5 tomato type Moneymaker, 10 paprika (*Capsicum annum*) type Yolo Wonder, 5 broccoli (*Brassica oleracea* var. *italica*) type Calabrese natalino, 8 butterhead lettuce type Mona, 8 zucchini (*Cucurbita pepo*) type Diamant F1 hybrid, 7 cucumber type Montea, 8 spinach type Matador, 5 aubergine (*Solanum melongena*) type Early Long Purple 3, 8 lettuce (*L. sativa* var. *crispa*) type Lollo rosso, 3 peppermint (hybrid *Mentha × piperita*), 3 basil, 3 chives (*Allium schoenoprasum*) type Polyvit, and 3 rosemary were used.

Statistical analyses. Tests were performed in order to identify possible effects caused by the fish and plant choice between the two cycles (bilateral). All data from the fish tank, clarifier and sump were combined, calculating the mean for each data set and cycle. Values were compared, using the Shapiro-Wilk test, followed by the T-test and Levene statistic, in the case of normal distribution. Otherwise, the Mann-and-Whitney test was performed to determine significant differences at the $p < 0.05$ level. All data were analysed by Microsoft Excel 2010 and the SPSS 20.0 statistical software package (IBM).

Results

Water parameters. The water parameters were not statistically significant (Table 2). Only slight differences were shown in conductivity, with 1018.79 µs (±246.26) in cycle I and 975.24 µs (±234.30) in cycle II, TAN 1.12 mg L^{-1} (±1.98) and 0.84 mg L^{-1} (±1.69), and NO$_3$-N with 9.25 mg L^{-1} (±5.67) and 7.28 mg L^{-1} (±4.95), respectively.

Table 2

Chemo-physical water parameters

Parameter	Cycle I	Cycle II
	Mean ± SD	Mean ± SD
Temperature [°C]	24.94[a]±2.30	25.42[a]±2.44
Oxygen [mg L^{-1}]	5.43[a]±2.48	5.32[a]±2.61
Oxygen sat. [%]	66.37[a]±31.55	65.92[a]±33.94
Salinity [‰]	0.51[a]±0.14	0.48[a]±0.13
Redox potential [mV]	189.53[a]±33.55	187.57[a]±33.54
Conductivity [µS]	1018.79[a]±246.26	975.24[a]±234.30
pH	7.79[a]±0.33	7.83[a]±0.32
TAN [mg L^{-1}]	1.12[a]±1.98	0.84[a]±1.69
NO$_2$-N [mg L^{-1}]	0.25[a]±0.24	0.23[a]±0.36
NO$_3$-N [mg L^{-1}]	9.25[a]±5.67	7.28[a]±4.95
Phosphate [mg L^{-1}]	1.37[a]±1.30	1.13[a]±1.04

Means (±SD), different letters in groups showing significant differences ($p < 0.05$).

The mean oxygen levels [mg L^{-1}] (Figure 2) in the different subsystems first slightly increased and then decreased. Values followed the curves for SE I, $y = 0.0015x+8.5344$ ($R^2 = 0.0035$), for SE II, $y = -0.0361x+8.0322$ ($R^2 = 0.1232$), and for SE III, $y = -0.0344x+7.8058$ ($R^2 = 0.2742$). In contrast, phosphate [mg L^{-1}] (Figure 3) showed, throughout SE I, SE II and SE III, increasing values, with SE I, $y = 0.0079x+0.0874$ ($R^2 = 0.323$), SE II, $y = 0.015x-0.5824$ ($R^2 = 0.377$) and, notably, SE III, $y = 0.0465x-3.7431$ ($R^2 = 0.745$). TAN [mg L^{-1}] also increased for SE I, $y = -0.0009x+0.0817$ ($R^2 = 0.153$), for SE II, $y = 0.0014x+0.0969$ ($R^2 = 0.041$) and for SE III, $y = 0.1027x-11.309$ ($R^2 = 0.420$).

Values for salinity [‰] and conductivity [µs] first increased (SE I and SE II) and remained stable during SE III (Figure 4). Salinity was expressed for SE I with $y =$

0.0011x+0.2954 (R² = 0.7651), for SE II with y = 0.0035x+0.1905 (R² = 0.9871) and for SE III with y = 0.0012x+0.4849 (R² = 0.4744). Conductivity was characterised for SE I as y = 1.9833x+643.09 (R² = 0.5664), for SE II as y = 7.285x+386.97 (R² = 0.9279), and for SE III as y = 0.5455x+1174.1 (R² = 0.0243).
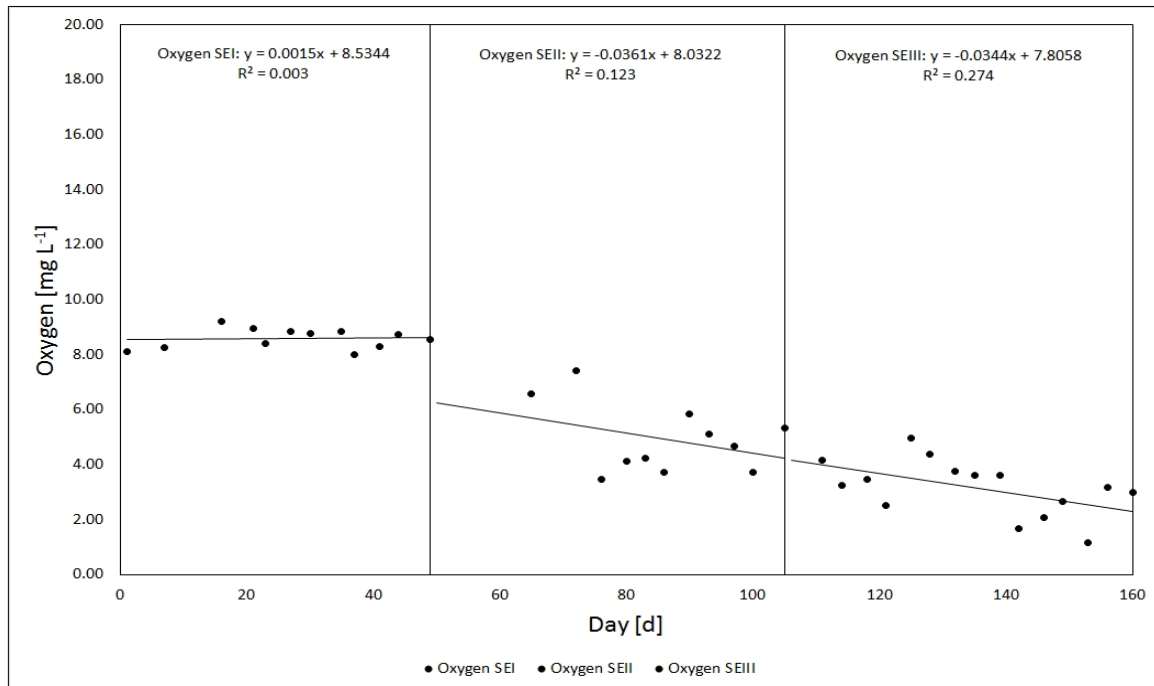
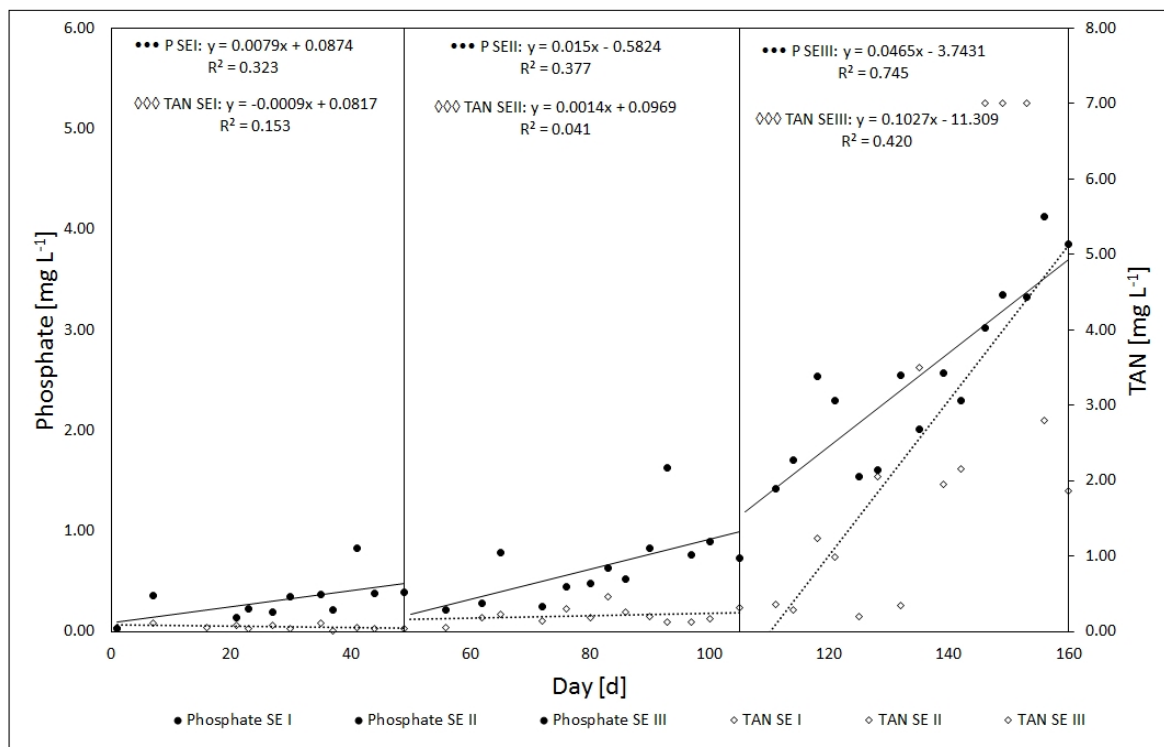Figure 2. Oxygen [mg L^{-1}] distribution in different sub-experiments (SE I, SE II, SE III).

Figure 3. Phosphate [mg L^{-1}] and TAN [mg L^{-1}] in different sub-experiments (SE I, SE II, SEIII).
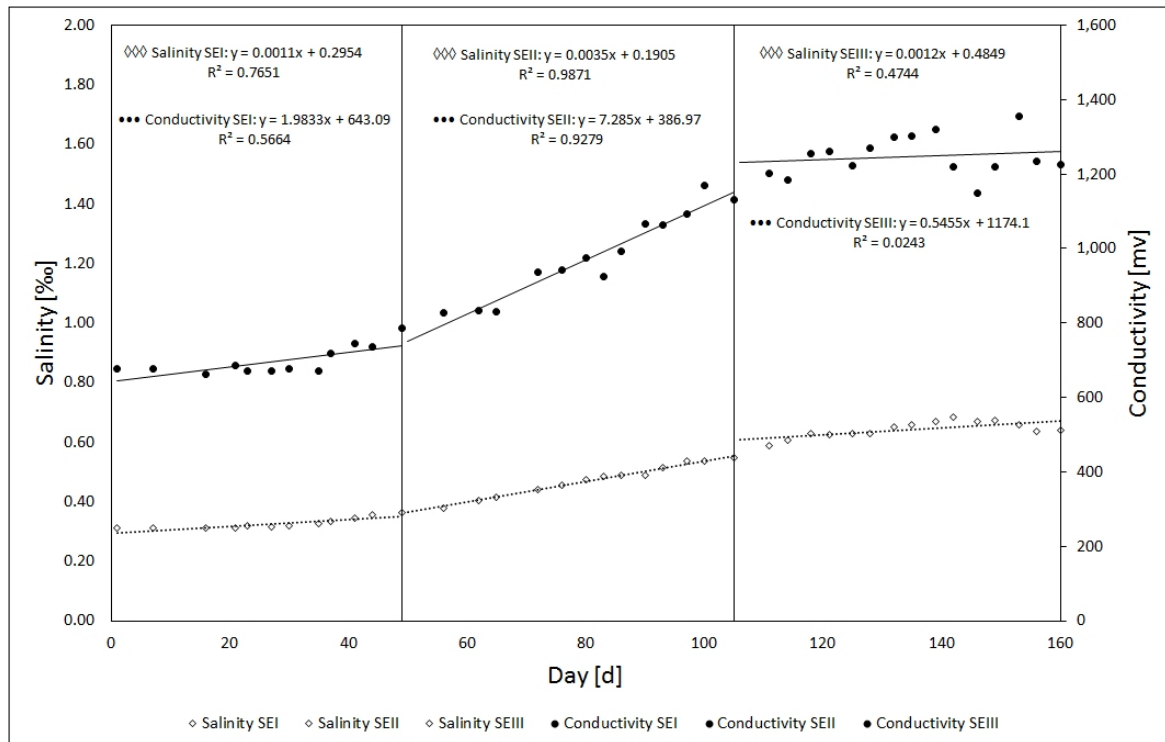
Figure 4. Salinity [‰] and conductivity [μs] in different sub-experiments (SE I, SE II, SE III).

Fish and plant growth parameters. Differences were seen in the final fish biomass with 24,448.57 g (cycle I) and 20,614.13 g (cycle II, Table 2). Biomass weight gain also varied between 24,249.57 g (cycle I) and 20,415.13 g (cycle II). The feed conversion ratio (FCR) was only slightly different, with 0.83 for cycle I and 0.93 for cycle II. Individual fish growth parameters (Table 3) were not significantly different ($p < 0.05$). The weight gain of *O. niloticus* was slightly different, with 60.93 g (±28.95) in cycle I and 51.29 g (±16.20) in cycle II. Figure 5 illustrates the weight gain exponential curve (mean) $y = 0.0034x^2 - 0.1767x + 2.5485$ ($R^2 = 0.99$) of *O. niloticus* fry.

Table 3

Individual fish growth parameters of cycle I (*O. niloticus*) and cycle II (*O. niloticus*)

Parameter	Cycle I	Cycle II
	Mean ± SD	Mean ± SD
Initial body weight [g]	0.50[a]±0.00	0.50[a]±0.00
Final body weight [g]	61.43[a]±28.95	51.79[a]±16.20
Weight gain [g]	60.93[a]±28.95	51.29[a]±16.20
SGR[1] [% day^{-1}] 154 d	3.04[a]±0.34	2.98[a]±0.21

Means (± SD), different letters in groups showing significant differences ($p < 0.05$).
[1]SGR = specific growth ratio [% d^{-1}] = (ln W_t - ln W_0) x 100/days.

The fish feed was adjusted to fish growth in SE I and SE II. In SE III, the daily amount of given feed started with 175 g and reached a maximum of 465 g, followed by a stable feed amount of 200 g in SE III (Figure 5). The specific growth ratio (SGR) showed only little variation, with 3.04% d^{-1} (±0.34) in cycle I and 2.98% d^{-1} (±0.21) in cycle II. Throughout the entire run of the experiment, there was a low mortality rate of 1.01% only in cycle II (Table 4).

In cycle I, the plants (total biomass of tomato, 20.03 kg) grew as expected. In cycle II, the chosen plants (especially basil, broccoli and chives) showed deficiencies, and the mortality was moderate.
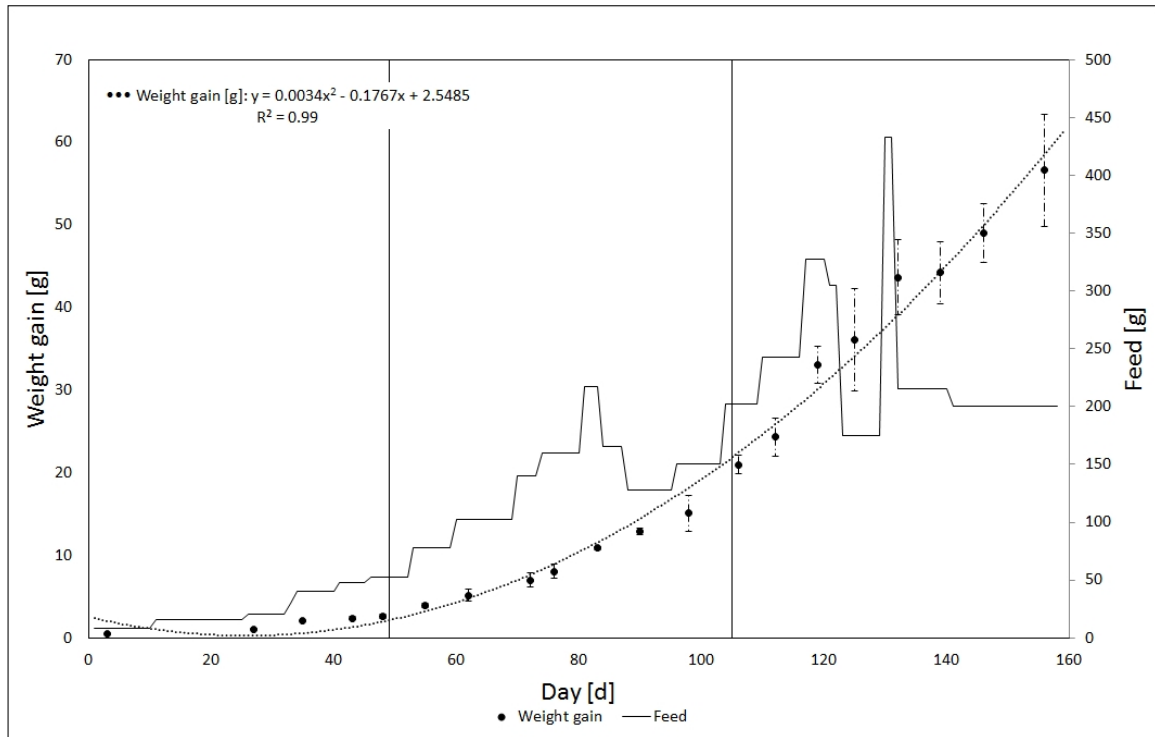
Figure 5. Weight gain [g] of *O. niloticus* (Means, ± SD) and fish feed [g] used (means) over 160 experimental days [d], divided into three sub-experiments (SE I, SE II, SE III).

Table 4

Fish biomass parameter (total values)

Recirculation unit	Fish species	Initial biomass [g]	Final biomass [g]	Stocking density [fish m^{-3}]	Biomass weight gain [g][1]	FCR[2]	Mortality [%]
Cycle I	*O. niloticus*	199.00	24,448.57	159	24,249.57	0.83	0.00
Cycle II	*O. niloticus*	199.00	20,614.13	159	20,415.13	0.93	1.01

[1]Biomass weight gain [g] calculated as difference from final biomass [g] and initial biomass [g].
[2]Feed conversion ratio (FCR) calculated as feed assignment [g] and biomass weight gain [g]$^{-1}$.

Discussion

System design. The present study describes a freshwater ebb and flow aquaponic system with an expected functional gravel substrate hydroponic unit, without the use of additional fertilizer. Such substrate systems can be built as open (wetlands) or closed (recirculation) systems. Scientific studies on closed ebb and flow aquaponic systems are scarce. Our system is particularly characterized by the hydroponic gravel substrate, in combination with a biofilter, as the most effective bioactive components. Consequently the chemo-biological processes, such as nitrification, functioned as expected. In accordance with the observed chemo-physical parameters that can indicate a stable run of an aquaponic system (see below), we identified the optimal fish feed input level to be 200 g per day.

The system's relationship between the aquaculture unit (1,800 L), the sedimenter (800 L), the biofilter (60 L volume biocarrier) and the hydroponic unit (480 L) was 2.25:1:0.075:0.6, with a fish tank to hydroponic unit factor of 3.75. Other characteristics of the system included low water exchange rates, refilling 10 L per day that was removed from the fish tank outlet for cleaning and through regular evaporation. The oxygen supply originated from aquarium air pumps with low energy input, and only a single low

energy water pump was used to provide stable water recirculation. The general advantages of the tested system are low water consumption and place autonomy, combined with low maintenance costs. Disadvantages include difficulties in identifying the optimal conditions for the combined fish and plant cultivation, because both affect each other, possibly resulting in suboptimal growth. According to Rennert et al (2011), fish and plants require different optimal conditions, for example pH level, making some plant species unsuitable for cultivation in a closed ebb and flow system.

Water parameters. The oxygen level [mg L^{-1}] was identified as a major important indicator for system stability, changing according to the varying fish feed input levels. The low fish feed input at the beginning of the experiments in SE I was under the optimal carrying capacity of the biofiltering capacity, and resulted in a slightly increasing oxygen level (y = 0.0015x+8.5344, R^2 = 0.003, Figure 2). With increasing feed input, decreasing oxygen values were observed in SE II (y = -0.0361x+8.0322, R^2 = 0.123). In contrast, SE III showed a more optimistic oxygen curve expressed as a slightly more positive linear equation (y = -0.0344x+7.8058, R^2 = 0.274). However, it must be kept in mind that after reaching a feed input of 465 g day^{-1} and a distinct drop in oxygen levels in the fish tank (first phase), the feed input was reduced to a constant 200 g in the second half of SE III (second phase). Also, the response appeared to be sluggish, resulting in a delayed parameter change during the run of the experiments. According to our data, the oxygen level was a suitable indicator for the system stability in the aquaponic system, although with a distinct time lag. Studies of Lennard & Leonard (2004) on a gravel bed ebb and flow aquaponic system demonstrated, in general, decreasing dissolved oxygen concentrations during a constant flow treatment and an ebb and flow situation, with better oxygen levels and less fluctuation at constant flow rates. However, the linear decrease of oxygen levels included several peaks and provided no indication of system stability. The fish were even fed with much less feed compared with the present experiment of 1.0% (first 6 days) and 1.5% for the remaining 15 days.

The chemo-physical water parameters for growing *O. niloticus* were in their optimal range (Pullin & Lowe-McConnell 1982) during the entire run of the experiments. The temperature was in its optimal range and did not distinctly differ during the sub-experiments. The oxygen levels were not significantly different between the sub-experiments and cycles (5.43 mg L^{-1} ±2.48 and 5.32 mg L^{-1} ±2.61). Tilapia (e.g. *O. niloticus*) have been recorded to be very tolerant of reduced levels of dissolved oxygen (DO), and short-term DO limits of 0.1 ppm were reported for *O. niloticus* (Pullin & Lowe-McConnell 1982). A growth-limiting effect was reported for *Sarotherodon mossambicus* at oxygen saturation levels below 32% and 25% (Pullin & Lowe-McConnell 1982). The observed minimum oxygen levels for *O. niloticus* did not reach less than 5.32 mg L^{-1} and 65.92% (cycle II). Thus, the temperature and oxygen levels met the requirements for *O. niloticus*.

The salinity [‰] and conductivity [µs] increased during the experiment, correlated to the amount of fish feed (Figure 4), and their levels were not significantly different between cycle I and II (Table 2). Due to the constantly increasing amount of feed in SE I, SE II and SE III (Figure 5), both salinity and conductivity values also increased (Figure 4), and remained more stable in SE III with the fish feed input of 200 g day^{-1}. This is in accordance with Lennard & Leonard (2004) where conductivity appeared to be stable at the end of their experiment, with higher values under the ebb and flow situation between 350-400 µs.

Tilapia species, in general, are also tolerant of different pH-values (Pullin & Lowe-McConnell 1982). Considering the alkaline conditions with pH values of 7.79 (±0.33) and 7.83 (±0.32), no negative effects on the fish growing parameters can be expected. The TAN [mg L^{-1}], NH_3-N [mg L^{-1}], nitrite [mg L^{-1}] and nitrate [mg L^{-1}] values were not toxic to the fish, due to the functional biological nitrification processes in the tested system. The phosphate concentration was also not significantly different between both systems (cycle I: 1.37 mg L^{-1} ±1.30 and cycle II: 1.13 mg L^{-1} ±1.04).

Fish growth. All water parameters enabled the optimal growth performance of Tilapia during the experiment. Consequently, only a very low mortality was found for *O. niloticus*. No significant differences of the growing parameter were shown between the recirculation units (cycle I and II). The fish growth is correlated to the protein content [%] of the feed. El-Sayed & Teshima (1992) found an optimum protein level of 45% for *O. niloticus* fry; at 50%, no further growth improvement occurred. The protein requirement of *O. niloticus* decreases with age. Abdel-Tawwab et al (2010) recorded the optimum growth performance of tilapia fry (0.4-0.5 g) at 45% crude protein, and a reduced requirement of 35% crude protein for the fingerlings (17-22 g) and advanced juveniles (37-43 g). The feed that we used in the present study contained 47% crude protein and 14% crude lipid, and was, therefore, close to the optimum levels for the cultured species.

The fish growth differed significantly between the sub-experiments. We can distinguish two different growth conditions for the fish. From SE I-II and the beginning of SE III, the feed intake was increased, in SE III, in the proportion of 232.5% (465 g = 2.50% feed per body weight day^{-1}, day: 130, 131) of the calculated body weight until the carrying capacity of the tested aquaponic system was reached, as can be seen in the strong drop in the oxygen level at days 132 and 135 in the fish basin. Fish growth under a steady state condition was observed at the end of the second phase in SE III. The growth performance of the fish in the tested aquaponic system was very good, as can be seen in the good feed conversion ratios (0.83, cycle I and 0.93, cycle II). The feed conversion directly depends on the feed assignment. Chowdhury (2011) clarified an optimal feeding regime for *O. niloticus* with a decreasing feed amount of 10-8% and 8-6% for juveniles (1.1 g) during the first and second week, 3% of the biomass for 80-115 g and larger fish, and 1.2% for fish over 260 g. The tilapia (0.5 g) were fed at feeding levels of 4% (SE I), 5% (SE II), and, later, at the near optimal feed input of 2.5% (SE III). This level was in accordance with an optimal run of the system, and an approximate amount of 200 g feed intake per day. The SGR of the fish was not significantly different. In general, the SGR of *O. niloticus* was slightly under the expectation (3.04% d^{-1} and 2.98% d^{-1}) in comparison with earlier investigations by Abdel-Tawwab et al (2010), with specific growth ratios from 3.289 to 4.287% d^{-1}. The optimum feed amount for our aquaponic system was tested at 200 g per day for the *O. niloticus*. Fish feed overload (> 200 g) affected the oxygen level and resulted in an apparent *O. niloticus* growth depression. However, the oxygen level is a decisive factor for a closed substrate aquaponic system, because it not only affects fish performance but also the functioning of the substrate biofilter, and has consequences for plant growth.

Plant growth. The plants performed differently during the run of the experiment. At the beginning, the growth was limited by the low feed intake in SE I, limiting the available nutrients in the system. The plant growth increased in SE II, which was followed by a growth depression in SE III, caused by the higher feed intake, followed by a decrease in the oxygen saturation levels and the appearance of an algae film in the hydroponic plant boxes. Even though the plant growth was under expectation, the tomato plants reached a yield of 20.03 kg in cycle I. Further investigations must verify the different plant growth parameters.

General aspects. The future development of sustainable aquaponic systems requires an economic environment with an adequate product market price (fish and plants) combined with a product quality comparable to or better than those from other aquaculture activities. However, as presented in our analyses, a number of additional influencing factors are responsible for the actual success (Figure 6). Of general importance is the system design that is directly responsible for the maximum possible output, the fixed and variable costs and the general investment. The design varies according to the type of aquaponics, the ratios of the involved components, system and management alterations, as well as the most important economic factors involved. However, the system design also has a direct impact on the environmental conditions within the system and on the underlying maintenance costs. The former are directly dependent on system

management issues, feed choice and use, and fish and plant choice, as well as on single or multiple age class or multispecies production in polyculture. Fish feed quality affects the overall system performance via nutrient parameters (phosphorus, ammonia, nitrite, nitrate, pH), fish and plant physiology, and welfare, as well as through possible disease outbreaks. Such a high number of biological variables make simple economic analyses of aquaponic production impossible, requiring not only economical but also biological background information.
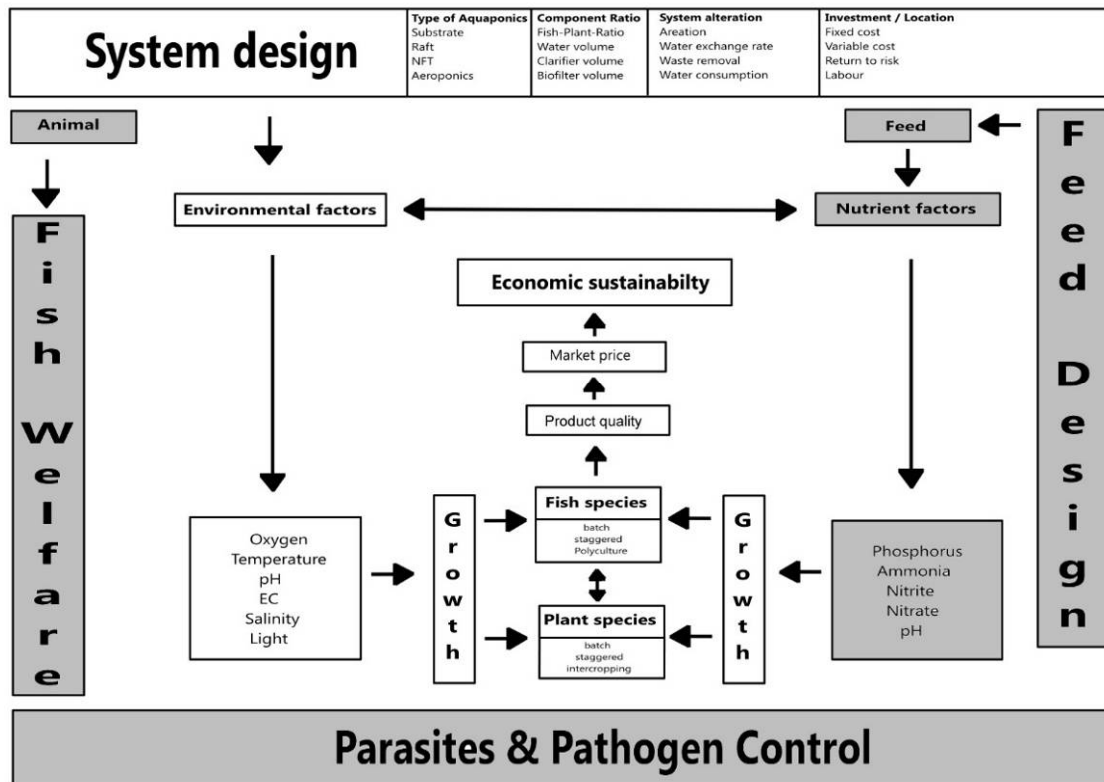
Figure 6. Significant factors that affect the economic sustainability of closed aquaponic systems. System design and the observed chemo-physical characteristics are described in part I.

Conclusions. The present study describes a low-tech closed ebb and flow gravel substrate aquaponic system with an optimal feed input level of 200 g day^{-1}. The observed water parameters resulted in good animal welfare and growth for *O. niloticus* in batch cultivation (FCR 0.83-0.93, 1% mortality). Fish feed overload (> 200 g) directly reduced the oxygen level, increased the salinity and conductivity, and resulted in an apparent *O. niloticus* growth depression. So far, only a few scientific studies have dealt with aquaponic cultivations, and none of them are directly comparable, owing to the fact that different systems, sizes and locations were used. Basic information on the most important factors influencing aquaponics is missing, preventing the transfer of results to other locations, systems and organisms. More detailed studies on fish and plant production within aquaponic systems are urgently needed.

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Authors:
H. W. Palm, University of Rostock, Faculty of Agricultural and Environmental Sciences, Aquaculture and Sea-Ranching, Justus-von-Liebig-Weg 6, D-18059 Rostock, Germany, e-mail: harry.palm@uni-rostock.de
R. Seidemann, University of Rostock, Faculty of Agricultural and Environmental Sciences, Aquaculture and Sea-Ranching, Justus-von-Liebig-Weg 6, D-18059 Rostock, Germany, e-mail: robert.seidemann@uni-rostock.de
S. Wehofsky, University of Rostock, Faculty of Agricultural and Environmental Sciences, Aquaculture and Sea-Ranching, Justus-von-Liebig-Weg 6, D-18059 Rostock, Germany, e-mail: sebastian.wehofsky@uni-rostock.de
Ulrich Knaus, University of Rostock, Faculty of Agricultural and Environmental Sciences, Aquaculture and Sea-Ranching, Justus-von-Liebig-Weg 6, D-18059 Rostock, Germany, e-mail: ulrich.knaus@uni-rostock.de