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Performance of a small-scale modular aquaponic system

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Abstract. Aquaponic systems aim to exploit the advantages of aquaculture and hydroponic systems. A reasonable fish production can be sustained and at the same time a wide range of green plants and vegetables will be beneffited from the nutrient-rich outflow of the fish tanks, providing nitrification services to reduce the ammonia and nitrite loads. In this paper, the performance of a small-scale modular aquaponic system was assessed for the critical initial running period of 14 days during September 2011, using lettuce, basil and Nile tilapia. It was evident from the results that mid-range fish stocking densities and accordingly nutrient loads are able to support a plant harvest at a ratio of 1:4 to 1:5 (amount of fish feed provided: harvestable biomass) in both species, depending on the initial size of the plants. Very small plants with sensitive root system should be avoided, as well as increased ammonia loads. Further improvements could be achieved by fine-tunning of the flow characteristics of the system, the standardization of water quality profile, the appropriate selection of substrate and the addition of extra biofiltration compartment.
Key Words: aquaponics, hydroponics, lettuce, basil, *Oreochromis niloticus*.

Introduction. Aquaponic systems combine technology and ideas from both aquaculture and hydroponic farming systems. By such combination, problems arising in aquaculture concerning solid removal and the requirement of steady availability of water rich in nutrients in hydroponic systems can be effectively tackled (Diver 2006; Nelson 2008). Fish are grown in freshwater tanks and the outflow rich in metabolic products and uneaten food (suspended solids, ammonia, nitrite and nitrate) are used as organic fertilizers and nitrogen sources for the cultivation of vegetables (Seawright et al 1998; Savidov et al 2007). By this process, the highly toxic substance to fish (i.e. the ammonia) is converted by nitrification bacteria in the hydroponic substrate and assimilated by the plants (Tokuyama et al 2004). In other words, the hydroponic substrate may effectively replace the conventional biofilter in a closed-recirculation system for fish production. Accordingly, fish and vegetables can be produced in a mutually-benefit water-reuse scheme.

Aquaponic systems in equilibrium between the aquaculture and hydroponic components can be highly efficient in biomass production of fish and vegetables in every scale of development and without the need for inorganic fertilizers, herbicides or other biocides (Nelson 2008). Such systems are also able to secure food for small-scale family-run producers (Pade & Nelson 2007) even in dry periods or arid/desert zones (Al-Hafedh et al 2008; Kotzen & Appelbaum 2010). Moreover, due to the lack of soil substrate such systems can be exploited in areas with poor or deteriorated soil quality or even in urban environments (Jorgensen et al 2009).

The aim of the present study was to assess the performance of a small-scale pilot modular aquaponic system for fish and green vegetables during the critical early phase of running.

Material and Method. The system-battery consisted of three main fish tanks each of them of 200 L. A rectangular channel of 25 L was mounted above each tank, where the plants were placed. A small electrical pump (2 L min^{-1}) was immersed in each tank, supplying water to the channels and the water was returning by gravity to the tanks (Figure 1a). In the hydroponic component (i.e. in the channels), water was flowing over their bottom at a steady rate dictated by the diameter and the position of the outflow hose. Perlite was used as cultivation substrate and nitrification bacteria substrate, floating above the water and green vegetables were planted in holes on the top of the channel (Figure 1b).

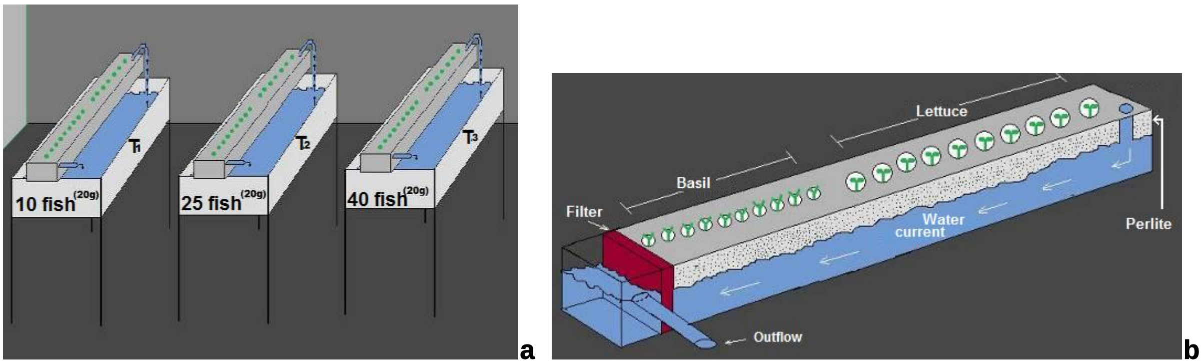


Figure 1. (a) Design of small-scale experimental aquaponic system (water circulation is highlighted by arrows) and (b) the hydroponic compartment.

The experimental process lasted 14 days on September 2011 for each of the three experimental groups. In all of them, ten lettuce (*Lactuca sativa* Linnaeus, 1758) and ten basil (*Ocimum basilicum* Linnaeus, 1758) plants were planted in each of the three channels at different mean weights: 0.12 g and 0.09 g (group 1); 0.22 g and 0.14 g (group 2); 2.47 g and 2.1 g (group 3). Juveniles of Nile tilapia (*Oreochromis niloticus* (Linnaeus, 1758)) were stocked at different densities and biomasses (shown together with growth performance figures in Table 3). Fish were daily fed with 1.5% of body weight twice a day in equal meals.

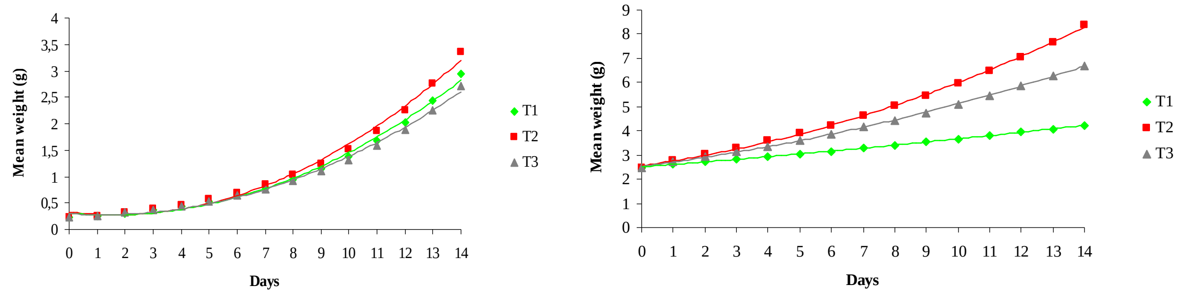
Ammonia, nitrites, nitrates, phosphates, pH and total hardness were monitored at a weekly basis and fish tanks were daily siphoned. Initially, only fish were stocked for a period of one month in order to balance the system and stabilise the nitrification ability of the perlite (at levels below 2 mg L^{-1} for ammonia). When ammonia and nitrite levels were stabilised, vegetables were planted. Water was partially replaced when nitrates exceeded 100 mg L^{-1}. Total mean weight gain, food conversion ratio (FCR) and specific growth rate (SGR) were calculated for tilapia and total mean weight gain and mean daily increase of biomass were calculated for the plants.

Statistical differences between tanks in each experimental group were examined by T-tests (P=0.05). Polynomial distribution was applied to describe the vegetative mass increases according to Walker et al (2001), Broadley et al (2003) and Boroujerdnia & Ansari (2007). Coefficient of variation for the fish weight was calculated and ANOVA was applied to detect differences in growth between different fish tanks. Single regression was applied to describe the relationship between feed and vegetative growth. All tests were performed by the StatistiX package and Microsoft Excel for Windows.

Results and Discussion. Ammonia in all T3 tanks was close to the 2 mg L^{-1} limit due to high fish stocking density. In the rest of the tanks (T1 & T2) ammonia never exceeded 0.5 mg L^{-1}. The values of nitrites, nitrates, phosphates and pH were always in acceptable levels.

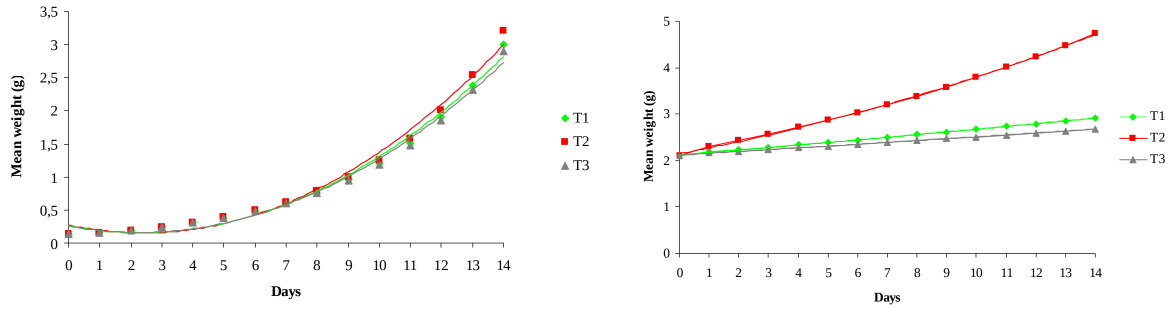
Both plant species failed to grow in the experimental group 1. In the rest of the groups, growth of lettuce and basil were evident in all tanks; however T2 showed the best performance in all cases, although no statistical differences were detected in all cases ($p > 0.05$) (Figures 2-3 and Tables 1-2).

The projected (theoretical) growth for a 90-day period for each species, experimental group and tank was estimated. Growth potential of lettuce for T2 was higher compared to T1 and T3 in both experimental groups ($p < 0.05$) (Figures 4a, b). In basil, the same trend was evident only for the experimental group 3, although not supported by statistical testing ($p > 0.05$) (Figures 5a, b).



a b

Figure 2. Mean weight of lettuce during the 14-day culture period in each of the three tanks (a) in the experimental group 2 and (b) in the experimental group 3.



a b

Figure 3. Mean weight of basil during the 14-day culture period in each of the three tanks (a) in the experimental group 2 and (b) in the experimental group 3.

Table 1

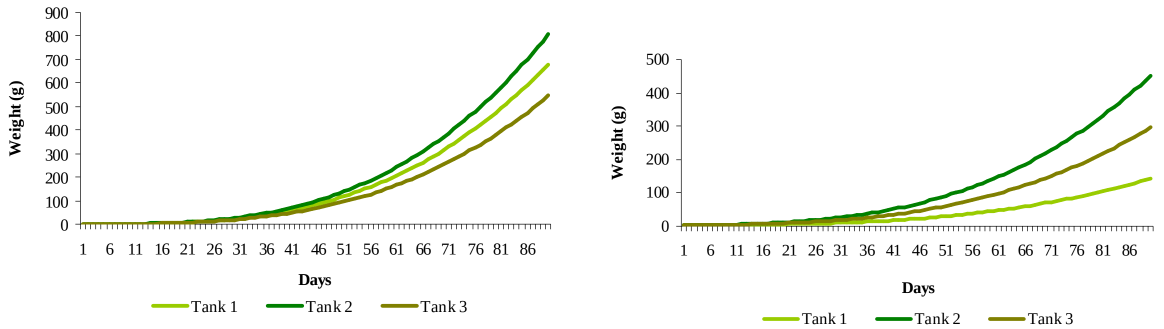
Growth of lettuce in different experimental groups and tanks of the aquaponic system

	Experimental group 1			*Experimental group 2*			*Experimental group 3*		
Tank	T1	T2	T3	T1	T2	T3	T1	T2	T3
Number of plants	10	10	10	10	10	10	10	10	10
Mean initial biomass (g)	0.12	0.12	0.12	0.22	0.22	0.22	2.47	2.47	2.47
Mean final biomass (g)	-	-	-	2.94	3.36	2.71	4.24	3.36	6.71
Mean net biomass (g)	-	-	-	2.71	3.13	2.48	1.77	5.90	4.24
Mean daily biomass growth (g)	-	-	-	0.19	0.22	0.20	0.12	0.42	0.30
Total net biomass (g)	-	-	-	27.1	31.3	24.8	17.7	58.8	42.4

Table 2

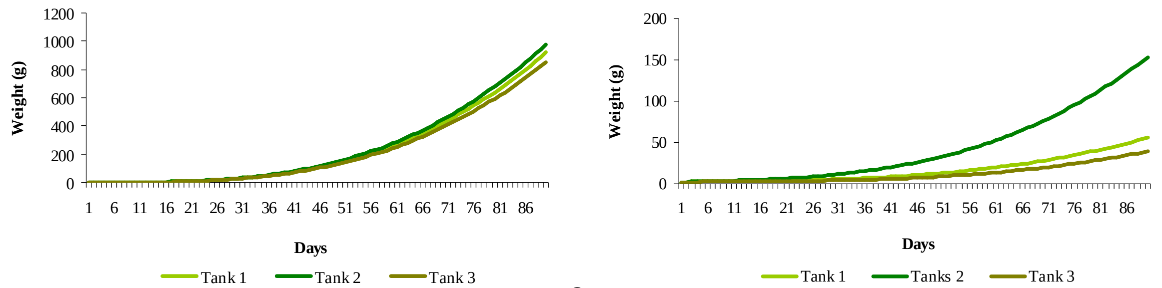
Growth of basil in different experimental groups and tanks of the aquaponic system

	Experimental group 1			*Experimental group 2*			*Experimental group 3*		
Tank	T1	T2	T3	T1	T2	T3	T1	T2	T3
Number of plants	10	10	10	10	10	10	10	10	10
Mean initial biomass (g)	0.09	0.09	0.09	0.14	0.14	0.14	2.1	2.1	2.1
Mean final biomass (g)	-	-	-	3.0	3.2	2.9	2.92	4.73	2.68
Mean net biomass (g)	-	-	-	2.86	3.06	2.76	0.82	2.63	0.58
Mean daily biomass growth (g)	-	-	-	0.20	0.22	0.20	0.06	0.18	0.04
Total net biomass (g)	-	-	-	28.6	30.6	27.6	8.2	26.3	5.8



a **b**

Figure 4. Projected mean weight of lettuce during a theoritical 90-day culture period in each of the three tanks (a) in the experimental group 2 and (b) in the experimental group 3.



a **b**

Figure 5. Projected mean weight of basil during a theoritical 90-day culture period in each of the three tanks (a) in the experimental group 2 and (b) in the experimental group 3.

Nile tilapia growth was evident in all experimental groups and tanks (see Table 3); however differences recorded during the 14-day on-growing period were not statistical different ($p > 0.05$). T1 of the experimental group 2 showed the lowest FCR and the highest SGR values among all groups and tanks, followed by T2 of the same group.

Table 3

Growth performance of Nile tilapia in the aquaponic system

	Experimental group 1			*Experimental group 2*			*Experimental group 3*		
Tank	T1	T2	T3	T1	T2	T3	T1	T2	T3
Number of fish	10	25	40	10	25	40	10	25	40
Initial mean body weight (g)	23	23	23	26.8	25.5	26	32.2	30.16	29
Stocking density (kg m^{-3})	1	2.5	4	1.34	3.18	5.2	1.6	3.76	5.8
Final mean body weight (g)	26.8	25.5	26	32.16	30.1	29	33.9	31.2	32.4
Total initial biomass (g)	230	575	920	268	637.5	1040	322	754	1160
Total final biomass (g)	268	637.5	1040	321.6	752.5	1160	339	780	1296
Net biomass (g)	38	62.5	120	53.6	115	120	17.4	27.5	136
FCR	1.36	2.07	1.73	1.13	1.25	1.95	1.53	1.51	1.55
SGR%	1.02	0.69	0.82	1.22	1.11	0.73	0.92	0.93	0.90

Both plant species of the experimental group 1 failed to grow after the 10th day, probably due to the sensitivity of the root system in such weight (0.12 g) to the hydraulic characteristics of the system. In aquaponic systems, the water flow in the vegetable compartment is affected by the FCR of the fish, as well as by the growth rate of the planted material (Endut et al 2010). In our case, planting of the perlite at this developmental stage seemed to be detrimental to them. On the other hand, when bigger lettuce and basil plants were used (experimental groups 2 & 3), growth was satisfactory.

Growth rate of both plant species was affected by the stocking density of fish (Tables 1 & 2), indicating a strong relation to the fish feed supply to the system. Although there was no statistical evidence to support the above statement for the actual 14-day experimental period, this trend becomes statistically significant for lettuce when projected to a 90-day time window.

Both lettuce and basil grew better in medium-range fish stocking densities (T2) in the 2nd and 3rd experimental groups. Reduced growth rate of plants in T1 was possibly due to the lack of the required nutrients due to the low fish feed inputs. On the other hand, reduced growth in T3 could be attributed to the increased ammonia levels. High ammonia values are counterproductive in the hydroponic cultivation of green plants and accordingly in aquaponic systems (Walker et al 2001) and only when the ionized form range between 10 and 20% of the total nitrogen, it benefits plant growth (Racocy et al 1992). Moreover, the frequent water replacements in order to keep ammonia at low levels, reduced nitrate levels as well which is the predominant nitrogen source for plants (Liedl et al 2004; Rakocy et al 2006). Therefore, in high fish stocking densities, biofiltration cannot be served solely by the perlite substrate and the addition of extra biofilter seems to be essential to convert the excess ammonia load and at the same time to keep the nitrite levels at levels of 100-200 mg L^{-1}.

In the 2nd experimental group, total vegetative harvest was 55.7 g (27.1 g of lettuce and 28.6 g of basil) for T1, 61.9 g (31.3 g of lettuce and 30.6 g of basil) for T2 and 52.4 g (24.8 g of lettuce and 27.6 g of basil) for T3. The total fish feed provided was 60.3, 143.25 g and 234 g, respectively. Accordingly, in the early stage of plant development (plants of 0.2-3 g), the optimum ratio of fish feed per g of vegetable biomass was 1:4. Ratios of 1:10 (as in T1) and of 1:3 (as in T3) resulted in lower harvests due to the lack of nutrients and the excess ammonia levels, respectively.

Similar harvest trend was also evident in the experimental group 3; however growth discrepancies where more intense. Growth rates in all tanks were lower compared to the previous experimental group, which is explained by the bigger plants that they were used. Total vegetative harvest was 25.9 g (17.7 g of lettuce and 8.2 g of basil) for T1, 85.2 g (58.89 g of lettuce and 26.31 g of basil) for T2 and 48.2 g (42.4 g of lettuce and only 5.8 g of basil). The total fish feed provided was 72.36 g, 169.25 g and 261 g, respectively. Differences in the early cultivation stage (14 days) were not statistically significant, however they were pronounced in the mid-run (up to 90 days). Accordingly, for bigger plants (3-8 g), the optimum ratio of fish feed per g of vegetable biomass was 1:5.

Conclusions. The daily vegetative growth both in lettuce and basil is dependent on the amount of feed provided to the fish tanks and optimum harvesting may be up to 5-fold, compared to the amount of feed. Small-scale aquaponic systems are capable of producing green plants or/and vegetables from fish feaces, excretions and uneaten feed, if water quality is continuously monitored and plant sizes are appropriately selected (0.22 g and 0.14 g for lettuce and basil, respectively). At the same time if an appropriate fish species is selected, such as the Nile tilapia, growth performance of fish is satisfactory in the low-mid range stocking densities (e.g. 1.0-3.76 kg m^{-3}) required to balance the aquaponic system.

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