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THE POTENTIAL OF AQUAPONICS AS FOOD PRODUCTION AND NUTRIENT RECOVERY SYSTEMS IN KENYA

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Abstract

Global challenges such as lack of arable land, soil degradation, water scarcity, nutrient depletion and climate change are compromising agricultural productivity. Besides, there is increased demand for innovative and sustainable food production systems to increase food productivity for rapidly growing population. Aquaponics is a new method of food production which uses aquaculture wastewater to produce crops, thus reducing the need for irrigation and provides nutrients for the growth of plants. This study examined the growth of sweet worm wood, pigweed and pumpkin and their ability as part of biological filters for intensive production of Nile tilapia. Physical and chemical parameters were monitored at the influent and effluent of the hydroponic system. The final wet weight of the plants was measured, and growth of fish monitored biweekly. The plants grew rapidly with no signs of nutrient deficiency during the experimental period. There was a significant variation in wet weight of the three plants ($P < 0.05$). Sweet worm wood had the highest weight which corresponded to high nitrate uptake by the plant with 73.43% ± 3.92 nitrate extraction efficiency. However, there was no significant variation in the reduction of ammonia, nitrates and nitrites ($P < 0.05$) in the three treatments. Phosphorus reduction varied among the three treatments ($P < 0.05$) with pumpkin extracting more phosphorus. The highest extraction corresponded with fruiting stage of the plant. The study indicates that aquaponics can recover nutrients sufficient for the growth of plants.

Keywords: *Aquaponic, biofilters,extraction, sustainable*

JEL Classification: *Q16, Q22, Q23,O13*

1 Introduction

Agriculture in the 21st century is facing multiple challenges; to produce more food to meet the demand of a rapidly growing population with a small rural labour force and limited land and water resources (FAO, 2009). In addition, increasing demand of food may not be met by conventional farming systems because of decreased arable lands, soil erosion, depletion of soil nutrient and wavering costs of energy (Bindraban et al.2012). The increasing population and decreasing crop yields is similarly putting additional pressure on an already fragile food production system. In Kenya, productivity of main crops such as maize is declining due to infestation of army worms, land degradation, unpredictable weather events such as prolonged dry conditions and continuous splitting of land between inheritors (Henze & Ulrichs, 2015). Assuring food security in the 21st century requires new, innovative and sustainable food production systems that can increase crop yields using limited land and water resources with little impact on the environment and biodiversity (Pearson, 2007).

Aquaponic system is a relatively new concept to food production and can provide solutions to the challenges facing conventional farming systems in the 21st century. The system consists of an integration of recirculating aquaculture system with hydroponics (production of plants in nutrient rich solution) where water is efficiently recirculated for maximum nutrient uptake by plants (Tyson et al. 2011). It is considered an innovative and sustainable solution of food production (Tyson et al. 2011). The general design of the aquaponic system as reviewed by Rakocy et al. (2006) is a single recirculating aquaponics system which focuses on fish and plant production with a biofiltration unit to oxidize toxic ammonia to nitrates. The biofiltration unit is reduced or completely reset by a large hydroponic unit and can be located indoors or outdoors (Love et al. 2014). The fish excrete toxic ammonia which is oxidized by bacteria into much less toxic nitrate that is consumed by plants and the filtered water is then channelled back to the fish tanks (Rakocy et al. 2006). Fish wastes from aquaculture provide essential nutrients to plants and in return plants serve as a biofilter for fish in a symbiotic relationship (Diver, 2006). The system therefore, serves the purpose of reducing pollution and increasing productivity using less land and water resources (Dediu, 2012). The high initial investment can be recovered if the system is operated continuously near maximum production capacity (Rakocy et al. 2006). When the aquaponic systems are used on subsistence scale, they can be a reliable method to provide a family of a cheap and nutritious food (Connolly and Trebic, 2010).

Aquaponics are one of the most efficient food producing systems since the amount of food produced per water volume is high. Studies have shown that 5 -10 times more output can be generated from the systems compared to conventional agriculture (Rakocy et al. 2006). Moreover, fish and vegetables can be produced without need for inorganic fertilizers, biocides or herbicides (Nelson, 2008). Food can also be secured for subsistence purposes (Pade and Nelson, 2007) in dry periods or desert zones (Al-hafedh et al. 2008), in regions with degraded soils and urban areas (Jorgensen et al. 2009). High yields in aquaponic systems is associated with higher planting densities, constant availability of water and lack of competition from weeds (Rakocy et al. 2006). Aquaponic trials in Alberta indicates that over 60 different crops can be grown in the aquaponic systems (Nelson, 2007) and almost all freshwater fish can be cultured in the systems except trout and salmon because they require high oxygen levels (Rakocy et al. 2006). There is potential for aquaponics systems to be profitable with high annual returns from plants and fish (Rakocy et al. 2006).

It is generally believed that aquaponic systems, with concomitant nutrients recovery, will become one of the widely accepted methods of sustainable food production in the future (Hu et al., 2012). Several studies in aquaponic systems have focused on improving the production of common herbs and vegetables in developed countries. However, there is little information regarding the production of plants in aquaponic systems developing countries particularly in semi-arid regions. This study compared the growth of sweet worm wood (*Artemisia annua*), pigweed (*Amaranthus dubius*) and pumpkin (*Cucurbita pepo*) in a small-scale recirculating system in a semi-arid area in Kenya. The production of fish and plants and nutrient extraction efficiency was determined.

2 Data and Methods

The experiment was conducted in a greenhouse to provide uniform conditions for the growth of both fish and plants in the aquaponic system. Three aquaponic systems were operated side by side for 3 months. Each aquaponic system consisted of 9 - 500L round plastic tanks filled with 400 L water and served as an aquaculture unit. Each tank was stocked with 5kg/m^3 of tilapia (*Oreochromis niloticus*). The fish were fed to satiation twice per day with 30% crude protein feed. The fish tanks were initially stocked with 450 *Oreochromis niloticus* with an average weight of 50g. The initial biomass in the recirculating aquaculture system was 22.5kg. An air pump (Aqua Forte, V-60) with a pressure of 0.03 Mpa and output 60 L/min was used to provide sufficient oxygen in the culture tanks and biofiltration unit. Water from fish tanks flowed through gravity to sand filters which were built using a 200L plastic barrel filled with pumice stones. The sand filter served as a mechanical filter which captured majority of the suspended solids from aquaculture tank. A 0.5HP pump was used to channel water to the biological filter. From the biological filters, water flowed by gravity to the three aquaponic treatments. Then the treated water flowed back to the fish rearing unit. The grow beds consisted of three rectangular timber made units (1m x 0.5 x 0.8m) supported by timber. The schematic diagram of the system is shown in Figure 1.

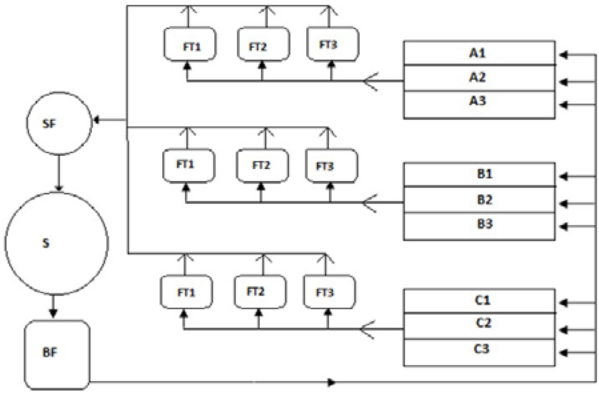
After three weeks, the different plant species (*Artemisia*, *Amaranthus* and *Curcubita*) were transplanted from seed trays to the experimental grow beds at a stocking density of 36 plants per square metre. The plants were grown in three grow beds in three replicates. Fish sampling was done biweekly to determine the length and weight. The growth performance of fish was assessed using standard formulas. The yield of the plants was determined by obtaining the weight of the fresh leaves which was the total biomass less the weight of roots.

2.1 Water sampling

Water samples were collected biweekly to determine the nutrient extraction efficiencies of the three plants. The samples were taken from the influent and effluent of each grow bed. The samples were analysed for ammonium, nitrate, nitrite, phosphorus using benchtop Hanna multiparameter photometer (HI83200) according to Nessler, cadmium reduction, diazotization and ascorbic acid method respectively. Physical parameters such as temperature, pH, dissolved oxygen and conductivity were also monitored twice daily using handheld probes (HACH HQ40d Portable meter, USA). Nutrient extraction efficiency of plants was calculated using the following equation:

$$Extraction\ efficiency\ (\%) = \frac{inlet - outlet}{inlet} \times 100$$

Figure 1 **Schematic representation of the aquaponic system. A, B & C: Grow beds, - A1, A2, A3; *Cucurbita*, B1, B2, B3; *Artemisia*, C1, C2, C3; *Amaranthus*, FT1, FT2 & FT3: rearing tanks, SF: Sand filter, S: Sump, BF: Biofilter**



Source: Author's design.

2.2 Data analysis

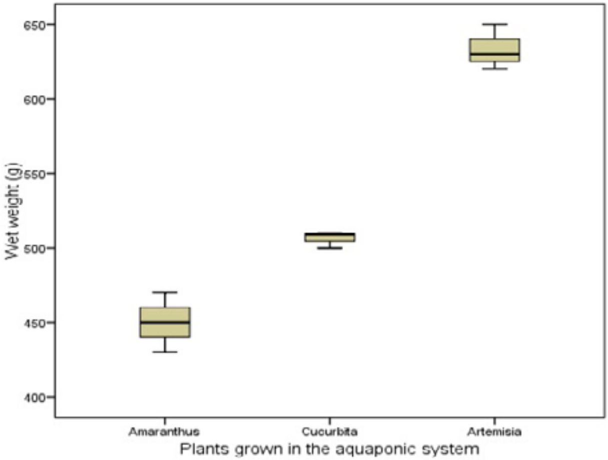
Data were expressed as mean ± S.E, statistical differences between treatments were tested using one-way analysis of variance (ANOVA) followed by a Tukey's comparison test at $p < 0.05$. Statistical analysis was performed using the SPSS software package (IBM Corp., SPSS statistics, version 21, Armonk, NY, USA).

3 Results and discussion

3.1 Plant and fish growth

The survival of the three plants was 100% during the experimental period. No plant disease was observed during the study period, however, *Amaranthus* was infested with aphids which were eliminated by spraying fresh water on the affected plants. Significant differences in growth of the three plants were observed (P 0.05). The total wet weight at harvest was 450g, 506g and 630g for *Amaranthus*, *Cucurbita* and *Artemisia* respectively (Figure 2). The low weight in *Amaranthus* was linked to the aphid infestation which affected the growth of some plants. Whereas additional wet weight in *Artemisia* was linked to high uptake of nitrates (Figure 3) which translated to high biomass.

Figure 2 **Wet weight (g) of plants at the end of the experiment**



Source: Author's calculations.

The results for the growth performance of Nile tilapia is shown in Table 1. Fish in *Cucurbita* and *Artemisia* based aquaponics had similar mean weight and grew significantly better than fish in *Amaranthus* based aquaponics (P<0.05). There were no significant differences (P<0.05) in SGR, FCR and survival rate among the treatments. However, growth performance parameters were better in *Cucurbita* and *Artemisia* based aquaponics. Fish mortality was only observed during the initial period of the experiment when the fish had not acclimatized with the culture environment. The feed conversion ratios (FCR) were within the range of recirculating aquaculture system (1-3) (Eding et al. 2001).

Table 1 **Fish production performance in the aquaponic system Different superscripts ($^{a,\,b}$) denote statistically significant differences between treatments (P < 0.05)**

Parameter	Treatment		
	Cucurbita	***Artemisia***	***Amaranthus***
Mean weight gain (%)	47.6 ± 7.02^{a}	47.3 ± 14.0^{a}	37.1 ± 7.47^{b}
SGR (% d^{-1})	0.98 ± 0.02^{a}	1.01 ± 0.07^{a}	0.94 ± 0.06^{a}
FCR	1.35 ± 0.06^{a}	1.38 ± 0.02^{a}	1.3 ± 0.02^{a}
Survival rate (%)	92.3 ± 3.55^{a}	93.0 ± 3.10^{a}	94.6 ± 2.05^{a}

Source: Author's calculations.

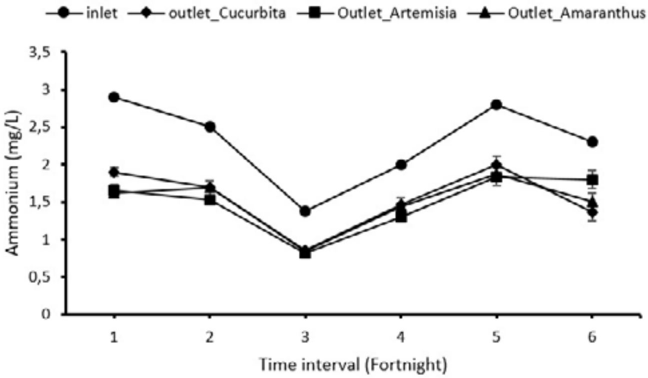
3.2 Water quality in the aquaponic system

The mean values of physical-chemical parameters of water from the aquaponic system were within optimal range for growth of the three plants. Temperature, pH and conductivity did not vary significantly among the aquaponic treatments. However, there was a significant variation in dissolved oxygen (DO) levels among the three plants($P<0.05$). The concentration of DO in the three aquaponic treatments ranged between 1.24 mg/L – 4.03 mg/L in the morning and 1.54 mg/L – 4.61 mg/L in the evening. Water temperature was maintained at 20.5 °C – 30.3 °C. Temperature in the fish tanks was 24.7 ± 0.87 °C in the morning and 28.7 ± 0.07 °C in the evening. pH values ranged between 7.49 -8.43 (mean 7.74 ± 0.27) in the *Curcubita* grow beds, 7.41 – 8.02 (mean 7.72 ± 0.22) in *Artemisia* and 7.49 – 8.12 (mean 7.76 ± 0.26) in *Amaranthus.* Temperature, dissolved oxygen (DO), pH and ammonia play a major role in the aquaponic system since they influence the physical and chemical composition of water. Therefore, proper management of these parameters can improve the general health and growth of both plants and fish in the system (Goda et al. 2015).

3.3 Nutrient uptake by plants

The plants had the ability to reduce nutrients from aquaculture wastewater as shown in Figure 3, 4 and 5. However, there was no significant differences in the removal of nutrients among the plants (P 0.05). Ammonia reduction was high during the initial growth period of the plants (Figure 3). The reduction might have been influenced by the poor performance of the biofilter during the start of the experiment because nitrate concentration was low (3.6 mg/L) for the development of seedlings. Xu et al. (1992) demonstrated that ammonium was the preferred nitrogen source when nitrogen concentrations were low while nitrate was preferred when nitrogen concentrations were high. The low extraction of nutrients during the initial growth phase could also be linked to poor root network system in the seedlings. With the growth of plants and full development of root network, the absorption of nutrients increased resulting in a decrease in nutrients from the grow bed outlets.

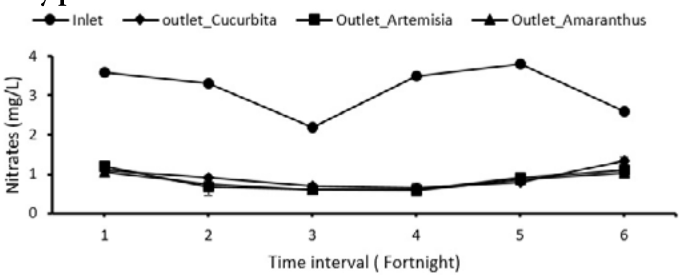
Figure 3 **Changes in ammonium in the aquaponic system during the study period**



Source: Author's calculations.

The low nutrient absorption ability particularly nitrates during the initial growth phase and increase in plant uptake rate with growth of plants has also been reported in pak choi aquaponic (Hu et al. 2015). Studies have shown that higher plant biomass translates to higher plant uptake rate resulting in higher nitrate removal efficiency (Snow & Ghaly, 2008; Hu et al. 2015). In this study, nitrate reduction decreased at week 10 for all the plant species because they had attained harvestable biomass. The highest reduction in nitrate levels was observed in *Artemisia* where the concentration was reduced from 3.17 mg/L – 0.8 mg/L (Figure 4), although there was no significant variation among the plant species. Hu et al (2015) investigated the effect of plant species on nitrogen recovery in aquaponic and reported that nitrogen uptake by plants played an important role in preventing the accumulation of NO_3-N in aquaponic systems.

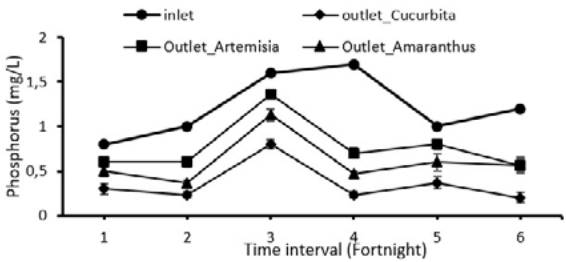
Figure 4 **Changes in nitrate concentration in the aquaponic system during the study period**



Source: Author's calculations.

Fish feed residues and fish waste are the major sources of phosphorus in aquaculture wastewater. In aquaculture waste water phosphorus occurs mainly as soluble and insoluble phosphates in organic and inorganic forms (Randall and Tsui, 2002). There was a general increase in influent phosphorus concentration with time. However, towards the end of the experiment the influent concentration of phosphorus reduced gradually (Figure 5). Extraction of phosphorus was consistent in all the treatments during the study period. *Cucurbita* was more effective in extracting phosphorus and the extraction increased with the growth period, at week 2 the plant absorbed 0.8 mg/L of phosphorus. At week 10 the plant extracted highest phosphorus (1.5 mg/L) from the influent water, the high extraction corresponded with the fruiting stage of *Cucurbita.*

Figure 5 **Changes in phosphorus concentration in the aquaponic system during the study period**



Source: Author's calculations.

Ammonia removal efficiency ranged between 33.44% – 36.45% (Table 2). Nitrate levels were reduced in the three aquaponic with time and were in the range of 69.84% – 70.43% at the end of the growth period. All the plant species were effective in removal of nitrates than ammonia. This was particularly true for *Cucurbita* which removed 70.06% of nitrates and 33.44% of ammonia. Phosphorus reduction was significantly high in *Cucurbita* with removal percentage of 70.35 % followed by *Artemisia* (49.22%). The reduction of 70.35 % is much higher than previous studies that reported 52.5% reduction (Lennard and Leonard, 2006) and lower than 87.1% to 95.1% reduction in barley hydroponic (Snow and Ghaly, 2008).

Table 2 **Nutrient removal efficiency by the three different plant species. The values are the average ofsix measurements.**

Nutrients (mg/L)		**Treatment**	
	Cucurbita	***Artemisia***	***Amaranthus***
Ammonium	33.44 ± 1.85 [a]	36.45 ± 2.67 [a]	35.29 ± 1.94 [a]
Nitrates	70.05 ± 4.86 [a]	73.43 ± 3.92 [a]	69.84 ± 4.55 [a]
Nitrites	38.28 ± 4.54 [a]	35.11 ± 4.00 [a]	39.76 ± 4.79 [a]
Phosphorus	70.35 ± 4.85 [b]	35.10 ± 6.31 [b]	49.22 ± 5.73 [b]

Source: Author's calculations.

The reduction of nutrients in the aquaponic system was linked to the utilization by plants and bacteria. In aquaponic systems, plants and bacteria play a significant role in water treatment. Plants uptake nutrient for plant growth from wastewater whereas nitrification bacteria that attach to the plant roots play a major role in nutrient cycle (Diver, 2006).

4 Conclusion

The study confirms that aquaponics can be reliable and sustainable food production systems in areas with limited land and water resources. Moreover, the system can recover nutrients from aquaculture wastewater sufficient for the growth of plants. The plants grew rapidly during the study period with no signs of nutrient deficiencies. No plant diseases were observed, although *Amaranthus* was infested by aphids which were eliminated by spraying freshwater on the affected plants. The extraction of nitrogenous compounds was not influenced by the type of plant. However, phosphorus extraction varied significantly among plants with *Cucurbita* extracting more followed by *Artemisia*. All plants were effective in removal of nitrates than ammonia. The extraction of nutrients was generally low during the initial growth period because the plants were still small with a poor root network system. As the plants grew and the network of roots developed, nutrient absorption increased. In general, the three plants had an extensive root network system which enabled them to absorb enough nutrients for growth. High biomass was observed in *Artemisia* due to high absorption of nitrates compared with other plants, although there was no significant difference in growth of the three plants. Based on the current findings, there is potential to improve food security through the production of both vegetables and herbal plants in aquaponic systems.

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