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ARTICLE

Further investigations of aquaponics using brackish water resources of the Negev desert

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Abstract – Outdoor, floating raft aquaponic systems using the brackish waters of the Negev Desert in Israel and a fresh water control are described. 7 m2 of vegetables and herbs were grown in each recirculating system with Tilapia sp. fish. Plant growth was excellent for species such as celery, Swiss chard, spring onions and watercress, and fish health and growth were good. Growth rates for fish were, however, low, with an upper limit of 1.1 g per day and would have increased with ad libitum feeding. Water quality was well controlled, and iron chelate was added to correct chlorosis problems. Leafy growth was very good, but fruiting could be improved with the addition of potassium (K) and other micronutrients.

Keywords – aquaponics, hydroponics, brackish water, Negev Desert

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Introduction

This paper focuses on aquaponics research undertaken in the Negev Desert, Israel, following initial experiments carried out in 2008/9 and reported in the 'Journal of Applied Aquaculture in December 2010 (Kotzen and Appelbaum). Whilst the initial research systems were established within an aquaculture greenhouse, the subsequent systems were established externally for two reasons: firstly, to ascertain how the plants and fish would react to being grown out of doors, and secondly, because the initial research established that poor airflow through the greenhouse during the warmer months resulted in poor growth for many plant species. This research continued the method of establishing two 'floating raft' systems, one with brackish water and a control with potable water. The use of brackish water is significant as many countries have underground brackish water resources, and more than half the world's underground water is saline. Whilst the amount of saline underground water is only estimated as 0.93% of world's total water resources at 12,870,000 km3 this is more than the underground fresh water reserves (10,530,000 km3) which makes up 30.1% of all freshwater reserves (USGS – The Water Cycle.) Underground brackish water resources in the Negev are estimated at 200 billion m3.

The brackish water used for the aquaponic systems was pumped from a local aquifer and was between 2680-4360 mg/l TDS (total dissolved solids) and with an electrical conductivity of 4187 - 6813 µS/cm (micro Siemens per cm). This water is considered to be slightly saline[1].

Materials and Methods

Two aquaponic floating raft systems were established in the first week of April 2011, and then again in the third week of July in an external yard area of the Bengis Centre for Desert Aquaculture (BCDA) at Sede Boqer in the Negev. This location included a brackish water system as well as a freshwater system (Figures 1 and 2). Both systems had the same layout with overall water volumes of approximately 6.1 m^3 each with plant tanks of 5 m^3 (a surface area of 7 m^2), filtration vessels of 0.1 m^3 and fish tanks of 0.9 m^3 (Figures 1 and 2). For each system, water from the fish tank flowed by gravity to the filters (biological and mechanical) where it then flowed by gravity into the plant tank and then into a sump whence it was airlifted and returned back to the fish tank. Aeration of the water occurred in the filters, at the sump and through two aerators in the fish tank and two located in the plant tank. The latter increased the vertical circulation of water in the tank, thus ensuring

[1] <2000µS/cm = non saline, 2000-4000µS/cm = slightly saline, 4000-8000µS/cm = moderately saline, 8000-16000µS/cm = highly saline and >16000µS/cm = extremely saline.

an even flow of nutrients and oxygen to the plant roots. An additional small tank (0.1 m3) was added to each system for the 2nd phase of the research. This tank was used to grow duckweed (*Lemna sp.*). Lemna can provide a high protein supplement to the fish diet, and these fast growing water plants may help to create an optimised aquaponic system where food grown within the system can be used to feed the fish. Leng 1999 for the FAO (Food and Agriculture Organization of the United Nations) notes after Gaiger et al., 1984 that 'fresh duckweed (and also the dried meal) is suited to intensive production of herbivorous fish' and that 'duckweed is converted efficiently to live weight gain by carp and tilapia' (after Hepher & Pruginin, 1979). Leng et al. 1995 further note the advantages of duckweed as a feed for fish: it can be fed fresh as it floats, it is efficiently used by tilapia and carp, and it is 'particularly low in fibre and high in protein when grown under ideal conditions and it is relatively inexpensive to produce'. Although duckweed was grown successfully in each system, the scope of this research did not allow for the feeding of the duckweed to the tilapia or for the systematic collection of data on intake and weight increases of the fish relative to the amounts of duckweed used as part of the diet. This research is considered important and will be carried out at a further stage.

The fish stocked in each of the fish tanks were 25 each of a red strain of Nile tilapia (*Oreochromis niloticus x blue tilapia O. aureus* hybrids). At the start in April 2011, the fish in each system had an overall weight of approximately 12 kg, with an average body weight of approximately 500 g. The systems were planted initially on the 9th of April and then again on the 20th of July 2011.

Water analysis tables, (Table 1, Table 2 and Table 3), illustrate the water quality at the start of the 1st installation/ 1st phase (21/04/2011) and at the end of the 1st installation (10/07/2011) and at the start (31/07/2011) and the end of the 2nd installation (15/09/2011).

Planting of the vegetables, herbs and melons was completed on the 10th of April 2011. These 'plug' plants were initially grown by Hishtil nurseries. Plants were placed as plugs in plastic net pots within the polystyrene rafts. The variety of species was greater than in the 2010 experiments, and the plants were located within groups of approximately 7 to 10 plants of each type within the polystyrene rafts. The planting area for each system was approximately 7 m^2 at approximately 15 cm centres between each plant with approximately 250 plants per system (approximately 28/m^2) and *included vegetables, melons and herbs as follows; aubergine (Solanum melongena), basil (Ocimum basilicum*), beetroot (*Beta vulagaris*), broccoli (*Brassica oleracea L. var. italica*), dill (*Anethum graveolens*), coriander (*Coriandrum sativum*), cauliflower (*Brassica oleracea var. botrytis*), fennel (*Foeniculum vulgare*), kohlrabi (*Brassica Oleracea Gongylodes Caulorapa*), leek (*Allium ampeloprasum porrum*), lettuce - various types (Lactuca sativa), lovage (*Levisticum officinale*), melissa (*Melissa officinalis L.*), melon (*Cucumis sp*.), peppers (bell) (*Capsicum sp*.), rocket (*Eruca sativa*), spring onion (*Allium cepa*), Swiss chard (B*eta vulgaris L. subsp. Cicla*), tomato (*Lycoper-sicon esculentum*) and watercress (*Nasturtium offici-nale*).

A comparison selection of vegetables was planted in loessal soil at the edge of a garden on Kibbutz Revivim and watered *ad libitum* as part of the garden. At planting, composted vegetable kitchen waste was added to the soil as a soil conditioner. Species included: basil (*Ocimum basilicum*), coriander (*Coriandrum sativum*), cauliflower (*Brassica oleracea var. botrytis*), fennel (*Foeniculum vulgare),* kohlrabi (*Brassica Oleracea Gongylodes Caulorapa*), leek (*Allium ampeloprasum porrum*) (Figure 5), lettuce -- various types (*Lactuca sativa*), peppers (bell), (*Capsicum sp*.), spring onion (*Allium cepa*), Swiss chard (*Beta vulgaris L. subsp. Cicla*) and watercress (*Nasturtium officinale*).

The performance of the plant species are noted in Table 6. The health and well being of the plants was noted during the experiment and at the end when the plants were extracted from the systems. Biomass and weight was not recorded as the conditions and numbers of plants in each system were not exact.

Fish were introduced into the systems on 15 April 2011, and fish feeding commenced by hand at 3 x 150g per system per week. The amount of fish food and the water temperature were recorded at each feeding. Feed nutrient values were as follows: crude protein 45%, carbohydrate, 28.6%, fat 12%, Ca 2.2%, P 1.2%, ash 8.5%, and fibre 2.5%. From June to September, the amount was increased to 3x200 g per system per week per system.

Results and Discussion

Water Quality

Water quality was tested for both the saline and freshwater systems at weekly or biweekly intervals throughout the two trials periods from the end of April to the middle of July and then for the 2nd phase from mid July until the middle of September.

Water Temperature and Dissolved Oxygen

The water temperature in the brackish and freshwater floating raft systems were 21°C at stocking; at the end of July, the temperatures had risen to 27.2°C, and then towards the end of September, the temperature rose to 29 °C, with an average over the whole period, April to September, of 24.85 °C.

Table 1. Water analysis of the brackish and freshwater systems, 1st phase

	Temp °C	pH	EC µS/cm	Salinity Ppm	NO3 mg/l	NH3/NH4 mg/l	NO2 mg/l	Fe mg/l	DO* mg/l
21/04/2011 – At Outset									
Average of Brackish Plant and Fish Tanks	21	8.38	3200	1.6	11	0.3	3	0	6.1
Average of Freshwater Plant and Fish Tanks	21	8.31	527	0	5	0.6	0.25	0	6.22
21/04/2011 - 10/07/2011 – Averages over whole period									
Average of Brackish Plant and Fish Tanks	22.5	7.8	3827	2.02	5.4	0.05	0.71	0	7.6
Average of Freshwater Plant and Fish Tanks	22.5	7.4	566	0	5.5	0.27	0.47	0	7.2

*DO = Dissolved oxygen

Table 2. Water analysis of the brackish and freshwater systems at the start of the 2nd phase

	Temp °C	pH	EC µS/cm	Salinity Ppm	NO3 mg/l	NH3/NH4 mg/l	NO2 mg/l	Fe mg/l	DO* mg/l
31/07/2011 – At Outset									
Average of Brackish Plant and Fish Tanks	29	7.64	5250	0.4	5.7	0	0.9	0	6.86
Average of Freshwater Plant and Fish Tanks	29	6.83	669	0	2.3	0	0.01	0	6.25
31/07/2011 - 15/09/2011 – Averages over whole 2nd phase period									
Average of Brackish Plant and Fish Tanks	27.2	7.73	5738	0.42	5.02	0	0.43	0	7
Average of Freshwater Plant and Fish Tanks	27.2	7.18	612	0	2.8	0.02	0.03	0	5.98

*DO = Dissolved oxygen

Table 3. Water quality averages over two growing periods from 21/04/2011 until 15/09/2011

	Temp °C	pH	EC µS/cm	Salinity Ppm	NO3 mg/l	NH3/NH4 mg/l	NO2 mg/l	Fe mg/l	DO* mg/l
Average of Brackish Plant and Fish Tanks	24.85	7.77	4783	1.22	5.19	0.02	0.57	0	7.30
Average of Brackish Plant and Fish Tanks	24.85	7.30	589	0	4.18	0.14	0.25	0	6.58

*DO = Dissolved oxygen

As noted in the previous article (Kotzen and Appelbaum 2010), water temperature affected both fish as well as plants, and in this respect, the timing of this experiment from April to September was better than the previous one which extended from December to June.

The health and growth of plants, in general, testified that the temperature of the water in the systems between 21 °C and 29 °C over the 5 month period was suitable both to the tilapia and to the plants, although most hydroponic experts agree that 20 °C to 21 °C is the optimum water temperature for growing plants hydroponically. Rakocy (2006), notes that the optimum temperature for tilapia growth is 28 – 30 °C. These temperatures were only reached in July/August with a maximum temperature of 29°C. On the whole, the water temperature range and average was far better for both fish and plants compared to the previous experiments undertaken in 2009/2010. As suggested then, it appears that, for the tilapia and most of the plants, a temperature of 24 – 25 °C is most probably optimum.

Water temperature affects the amount of dissolved oxygen (DO) it can hold. Cooler waters are more efficient at carrying dissolved oxygen (DO), and thus, an increase in DO may be required for fish in warmer waters. The DO levels in the systems increased from the outset in April, brackish 6.1 mg/l and fresh water 6.22 mg/l, with an average over the 5 months of brackish 7.6 mg/l and freshwater 7.2 mg/l. Popma and Masser (1999) note that tilapia can survive routine dawn DO concentrations of less than 0.3 mg/L, which is considerably below the tolerance limits for most other cultured fish. They furthermore note that ‘growth was not further improved if additional aeration kept DO concentrations above 2.0 to 2.5 mg/L.’ Rakocy (1989) states that ‘DO, which should be maintained at 5mg/litre for good tilapia growth, is the primary limiting factor for intensive tank culture.’ Rakocy furthermore importantly notes that 1000 lbs (450 kg) of tilapia ‘would consume 45 grams of O_2/hour at resting, but maximum oxygen consumption may be at least three times higher (135 grams O_2/hour).’ Tilapia, as a warm water fish (species that grow best at temperatures above 80 °F/26.6 °C), can tolerate lower DO concentrations than coldwater fish (species that grow best at temperatures below 60 °F/15.5 °C). Buttner (1993) suggests that ‘as a rule of thumb, DO should be maintained above 3.0 mg/L and 5.0 mg/L for warm and coldwater fish, respectively.’

pH

pH is an important factor, especially for the uptake of nutrients by the plant roots, as it affects the solubility of nutrients, especially trace metals such as iron, manganese, copper, zinc and boron. The optimum acceptable pH range for plants in hydroponic systems is pH 5.5 – pH 6.5 since the uptake of these nutrients decreases above pH 7.0. On the other hand, the solubility of phosphorus, calcium, magnesium and molybdenum sharply decreases at levels lower than 6.0. The optimum pH for plants is considered to be 7.0. This takes into account the fact that the bacteria that perform the nitrification process which is required to transform the ammonia produced by the fish into nitrite and then nitrate which then feeds the plants work best at between pH 7.0-9.0 (Rakocy, Buttner *et al.*). Rakocy (2006) thus suggests that pH 7.0 provides the best compromise between fish and plants.

At the start, the pH for the two systems were 7.7 (brackish) and 7.5 (fresh water) and quickly rose to 8.31 and 8.38, respectively, over a two week period, remaining at slightly below this level for a month, and then, as the system dropped in both systems to around pH 7.5. In June, after approximately 6 weeks, the pH started dropping in the freshwater system, where on the 24th of June the pH was 6.67, whilst for the brackish system, the pH remained alkaline at 7.86. Despite fluctuations in both systems, the pH in the freshwater system remained generally lower than that of the brackish system. The overall average over 5 months for the brackish system was pH 7.7 and fresh water pH 7.3. The pH range was suitable for the tilapia, but some plants may have been affected by a restricted uptake of nutrients as evidenced by chlorosis as a result of chlorophyll inhibition and/or iron deficiency.

Salinity/Electrical Conductivity (EC)

Both the electrical conductivity (EC) in µS/cm and the salinity in parts per million (ppm) were recorded for each system. At the beginning of the trials in April, the electrical conductivity (EC) of the floating raft brackish system was 3200 µS/cm, with an average of 3827 µS/cm from April until July, an average from July to September of 5250 µS/cm, and an overall average April until September of 4783 µS/cm. This increase in salinity is likely to have occurred due to the topping up of the system with additional geothermal brackish water, which itself varies from time to time at a peak of over 6800 µS/cm, and because of evapotranspiration and loss of water. Salinity measured in ppm commenced in April at 1.6 ppm, with an average of 2.2 ppm during April to July and an overall average April to September of 1.22 ppm. The EC for the freshwater system was, at the outset, 527 µS/cm, with an average April to July of 566 µS/cm and an overall average April to September of 589 µS/cm. Salinity measured in ppm was 0.0 throughout the period. As noted in Kotzen and Appelbaum (2010), Rakocy (2006) advocates that although in hydroponic solutions, EC should be 1500 to 3000 µS/cm, in aquaponic systems, EC should be between 300 and 600 µS/cm. However, both the tilapia and, on the whole, most of the selected plants performed well in the brackish water systems at EC levels close to and above 5000 µS/cm.

Nitrate (NO_3^-)

In the brackish water floating raft system, the NO3 started out at 11.0 mg/l with an average April to July of 5.4 mg/l and April to September of 5.19 mg/l. At the outset, NO3 in the freshwater system measured 5.0 mg/l, with an average April to July of 5.5 mg/l and April to September of 4.18 mg/l. Thus, the nitrate (NO3) nutrient supply to the plants in both the brackish water and fresh water systems were very similar. Visvanathan et al. (2008) and Mullen (2009) note an upper lethal limit of about 500 mg/l. Liedl et al. (2004) and Rakocy et al. (2006) suggest that, for plants, acceptable nitrogen levels, at the outset, would have been best at around 100 mg/l and, during growth, 200mg/l, but the apparent health of most of the plants, especially the leafy vegetables, indicated that even these low average levels of nitrate around 5.0 mg/l were enough to produce healthy vegetation and especially in the Swiss chard, celery, spring onions and lettuce. Increasing the fish density would have increased the nitrate supply and would have, most probably, further increased the growth of most of the vegetables and herbs. Increasing fish densities is indeed possible, and as noted previously (Kotzen and Appelbaum, 2010), Rakocy (2010) suggests that it is viable to stock tilapia at around 75 to 150/m3 of water, depending on the species.

Ammonium (NH_4^{-+})

At the outset, on the 9th of April, NH_3/NH_4^{-+} levels were 0.3 mg/l in the brackish water system and 0.7 mg/l in the freshwater system, as compared to the systems in 2010, which were 60.5 mg/l in the brackish water system and 1.87 mg/l in the freshwater system. The average levels of NH_3/NH_4^{-+} from April to July for the brackish system were 0.05 mg/l and 0.27 mg/l for the freshwater system, decreasing in levels over the months to averages for the whole period from April to September of 0.02 for the brackish water system and 0.14 for the freshwater system. Control of ammonia is extremely important for fish health. Ionized ammonia (NH_4^{-+}) stimulates plant growth, but very low levels un-ionized ammonia (NH_3) may cause stress and death of fish. It is generally recommended that the total level of NH_3 should be kept below 0.02 mg/l, but this level is dependent on pH and temperature. At an average temperature around 25 °C, NH_3 for waters of pH 7.0 and pH 7.5 should be kept below 3.5 mg/l and 1.1 mg/l, respectively. Levels can be reduced by: lowering stocking density, reducing feeding, improving biological filtration, use of ion exchange materials to remove ammonia selectively and by dilution by water change. (OATA 2011) As noted in Kotzen and Appelbaum (2010), ionized ammonia (NH_4^{-+}) is non-toxic to fish at levels that are likely to occur in recirculating aquaculture systems and is usually safe for most aquatic species in concentrations up to 100 mg/l.

Fish Production

Between April and May, the fish were fed 150g of fish food, 3 times a week, with a total of approximately 450 g per week. Thus, each fish consumed approximately 18 g of food each week. From June to September, the amount was increased to 200 g, 3 times per week, with a total of 600 g per week, and thus approximately 24 g per fish per week for an average weight of each fish at 500 g. It is noted that the fish would have eaten more if the food was provided *ad-libitum*. This was the case in the 2010 experiments (Kotzen and Appelbaum) where similar sized fish consumed up to 900 g per week in the warmer months, thus an additional 12 g per fish per week. All the tilapia in the freshwater system remained healthy, with two fatalities in the brackish water system towards the end of the experiment in the middle of September with one pregnant female, which was removed to a separate container.

On the 12th of April 2010, the average weight of the fish in the brackish water tank was 521 g and in the freshwater tanks, 495 g (Table 4). When weighed on the 24th of August 2011, the average weight of the brackish water fish was 625 g, and of the freshwater fish was 646 g. This is an average increase of 104 g for the brackish water fish and 151 g for the freshwater fish over 133 days (Table 4). This equates to an increase of 0.78 g/day/fish for the brackish water system and 1.1 g/day/fish in the freshwater system. These weights would have increased with *ad libitum* feeding. This is borne out by research by Rakocy and McGinty (1989) where tilapia can increase their weight by 1.5 to 3.5 g per day depending on stocking rates. It is interesting to note that, in the previous experiment (Kotzen and Appelbaum 2010), the freshwater fish also had a greater weight increase compared to the brackish water fish. The purpose of this research, however, was not to maximize fish growth but to ascertain whether the fish and plants would do well under the outdoor conditions and the cleansing regime of the water created by the system and the plants.

Plant Production

The first planting was completed on the 10th of April, and for two weeks afterwards, intermittent rain and a heavy downpour caused some damage and damping off of some plants, especially the smaller herbs with very small leaf areas. However, this did not affect most of the plants. The intention was to use insect netting over the plant container. This was not done as insect damage was minimal, but if it had been installed, the effects of the heavy rain would have been negated. The plant results shown in Table 6 are discussed relative to observations on the 22nd May 2011, 27th July (the week when the systems were replanted) and over the period of the 2nd phase planting. Monthly outdoor air temperatures, relative humidity and solar radiation data for the site are noted in Table 5.

Table 4. Fish weights in the brackish water and freshwater floating raft systems

Brackish Water System Averages in grams			Fresh Water System Averages in grams		
At Outset 12/04/11	**Finish 24/08/11**	**Increase over 133 days**	**At Outset 12/04/11**	**Stage1 finish 24/08/11**	**Increase over 133 days**
521 (25 fish)	625 (22 fish)	104 g 0.78 g/fish/day	495 (25 fish)	646 (25 fish)	151 1.1 g/fish/day

Table 5 Climatic data for Negev area – extracted from 'BGU weather station' 2

	April minimum maximum average	**May minimum maximum average**	**June minimum maximum average**	**July minimum maximum average**	**August minimum maximum average**	**September minimum maximum average**
Air Temperature [C°]	5.1 37.6 20.08	12.4 41.0 21.8	15.7 38.5 25.01	15.7 35.4 26.03	18.0 36380 26.48	17.8 33.10 23.78
Humidity [%]	22.00 92.00 52	9.0 100 54.8	8.0 95.0 48.71	8.0 93.0 50.61	8.0 93.0 64.6	23.00 100 67.67
Radiation [Watts/m²]	0.0 1043 288.57	0.0 1058 184.7	0.0 1035.0 33118	0.0 1025.0 310.90	0.0 1088.0 296.82	0.0 959.0 260.38

Table 6 Results of plants in brackish and freshwater floating raft systems
(√√√ = Excellent, √√ = Very Good, √ =Good, O = Fair)

English Name	**Latin Name**	**Brackish System May (M) July (J)**	**Freshwater System May (M) July (J)**
Aubergine	*Solanum melongena*	√ (M) Slightly weak but flowering √ (J) small plant 60+ cm tall, bigger fruits – better than fresh water	√ (M) √ (J) small plant 45 cm tall, small fruit
Basil	*Ocimum basilicum*	√√√ (M) √√√ (J) leaves 65 cm+ and good root system, flowering/seeding	√√√ (M) √√√ (J) leaves 65 cm+ and good root system, flowering/seeding
Beetroot	*Beta vulagaris*	X (M) X (J) poor bulbs, plants and roots	XX (M)
Broccoli	*Brassica oleracea 'italica'*	O (M) O (J) some florets formed	XX (M)
Cabbage	*Brassica oleracea*	√ (M) small O (J) small head and poor root system	√ (M) O (J) small head and poor root system
Cauliflower	*Brassica oleracea var. botrytis*	O (M) O (J) some florets formed	X (M) XX (M)
Celery	*Apium graveolens*	√√ (M) √√√ (J) leaves 70 cm+ strong root system	√√√ (M) √√√ (J) leaves 70 cm+ strong root system
Chard (Swiss) (Mangold)	*Beta vulgaris. 'cicla'*	√√√ (M)	√√√ (M) √√√ (J) leaves 65 cm strong root system
Coriander	*Coriandrum sativum*	X (M) some lost in rain/damping √ (J) leaves 25+ cm, strong roots	XX (M) lost in rain/damping
Dill	*Anethum graveolens*	XX (M) lost in rain/damping	XX (M) lost in rain/damping
Fennel	*Foeniculum vulgare*	XX (M) lost in rain/damping	XX (M) lost in rain/damping

[2] On site data extracted by the author from data supplied by the Department of Man in the Desert, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev.

English Name	**Latin Name**	**Brackish System May (M) July (J)**	**Freshwater System May (M) July (J)**
Kohlrabi	*Brassica oleracea*	√ (M) small √ (J) small bulbs, poor roots	√ (M) small
Leek	*Allium ampeloprasum porrum*	√√√ (M) √√√ (J) leaves 65 cm+, strong roots stronger than fresh water system	√√√ (M) √√√ (J) leaves 50 cm+, strong roots
Lettuce Various types	*Lactuca sativa various types*	√√√ slight chlorosis (M) √√√ (J) good heads, some bolted	√√√ slight chlorosis (M) √√√ (J) some bolted
Lovage	*Levisticum officinale*	√√√ (M) √√√ (J) leaves 60 cm+, strong roots	√√√ (M) √√√ (J) leaves 60 cm+, strong roots
Melissa	*Melissa officinalis L*	O (M) chlorotic √ (J)	O (M) chlorotic
Melon (Galia type)	*Cucumis sp*	√ (M) flowering O (J) fruiting, some chlorosis	O (M) chlorotic
Pepper (Bell)	*Capsicum sp.*	√ (M) √ (J) smallish plants, strong roots - good fruits	√√ (M)
Rocket (Arugula)	*Eruca sativa*	X (M)	X (M)
Spring Onion	*Allium cepa*	√√√ (M) √√√ (J) leaves 65 cm+, strong roots	√√√ (M) √√√ (J) leaves 65 cm+, strong roots
Thyme	*Thymus vulgaris*	O small (M) √√ (J) leaves 30+ cm, poor stubby roots	XX (M) (J)
Tomato	*Lycopersicon esculentum*	O fruiting (M)	√√ (M) √√ (J) ripe fruits
Watercress	*Nasturtium officinale*	√√√ (M) rampant	√√√ (M) rampant √√√ (J) rampant

The growth of the plants in the two aquaponic systems as compared with those grown in soil was remarkable. All the plants in the aquaponic systems were more advanced, larger and healthier in the aquaponic systems, including the leeks, kohlrabi, cabbages, lettuce, cauliflower, spring onions and the various herbs (Figure 3). The leeks (*Allium ampeloprasum porrum*) grown in the water (Figure 4) were at least five times the size (width of stem) of those grown in the loessal soil (Figure 5).

Unlike the research reported in 2010 (Kotzen and Appelbaum) where the study was undertaken within an existing aquatic greenhouse, where ventilation was poor, this research was carried out of doors. This meant that the plants were subjected to greater air temperature fluctuations, between day and night, as well as to lower humidity levels. However, the maximum temperatures reached and their duration was markedly reduced from the plant-unfriendly levels of the greenhouse. This was further helped by the periodic shading effects of the surrounding trees (with light foliage), which reduced the duration of direct sunlight. (Refer to Table 5 for local climatic conditions over the period of the research.) On the whole, these conditions were much more appropriate for the plants. The outdoor environment was also superior in terms of insect and rodent damage where little damage was in evidence. As expected, pollination by wind and insects was also superior in the outdoor systems. Chlorosis occurred in a number of plants species due to the lack of iron. Very little or no chlorosis occurred in the basil, chard, spring onions and watercress in either systems. As suggested by Rakocy et al. (2004), iron chelate (Fe2+) was added after the 2nd phase planting. Rakocy et al. (2004) suggest that iron chelate should be added at 2 mg/l. 75 g of iron chelate (Fe-EDDHA3 -'Geogold Sak 6 CS by 'Tapazol') was added directly into the plant growing tanks in each system over a 3 week period. Water testing did not show the presence of Fe above 1 mg/l, but the plants responded to the treatment, and thus, additional Fe was not added. The water immediately turned red and remained red whilst chlorosis was dramatically reduced in both systems without any evident detrimental effects to the tilapia.

The plant species that were most successful included basil (*Ocimum basilicum*), celery (*Apium graveolens*) (Figure 6), leeks (*Allium ampeloprasum porrum*) (Figure 4), lettuce (*Lactuca sativa* various types), Swiss chard (*Beta vulgaris. 'cicla'*), spring onions (*Allium cepa*) (Figure 7), and watercress (*Nasturtium officinale*).

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[3] EDDHA or ethylenediamine-N,N'-bis(2-hydroxy-phenylacetic acid) is an iron-chelating chemical

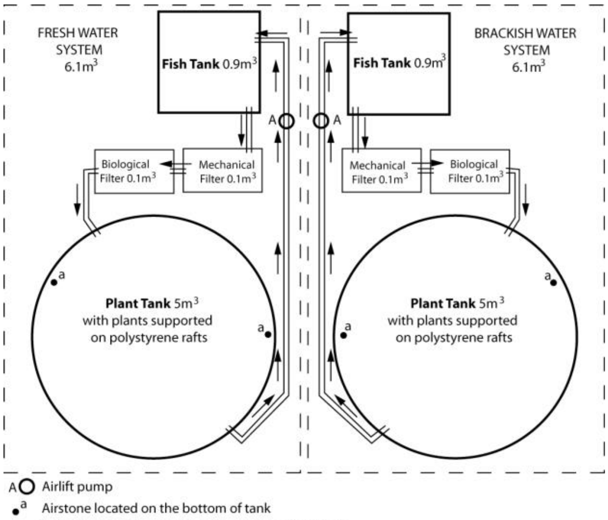

Figure 1. Diagram of aquaponic systems

Figure 2. Photographic view of aquaponic systems

Figure 3. Photograph of plants within system at maturity

Figure 4. Photograph of leeks grown in the aquaponics systems. (Compare with soil grown leeks in Figure 5), July 2011

Figure 5. Photograph of leeks grown in soil and planted at the same time as those in the aquaponics systems, July 2011

Plants that did well included aubergine (*Solanum melongena*), bell pepper (*Capsicum sp*.), kohlrabi (*Brassica oleracea*) and tomato (*Lycopersicon esculentum*) as noted in Table 6.


Figure 6. Photograph of mature celery plant shown within polystyrene raft with healthy root and leaf growth


Figure 7. Over mature spring onions at harvest in July 2011

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