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Development of aquaponic systems for space and water efficient food production

Pilot project final report

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Introduction

A pilot project to investigate the viability of aquaponic systems for sustainable food security and/or micro-enterprise in the Occupied Palestinian Territories (OPT) was launched in March 2011 at the Al-Basma centre in Beit Sahour, governorate of Bethlehem. Aquaponics is the fusion of recirculating aquaculture (production of food fish) with hydroponic plant growth (production of fresh vegetables and fruits) in a single system, in which fish wastes provide nutrition to the plants, and microbial activity and plant growth.

Factors leading to the development of this project were the potential benefits offered by aquaponic systems in the Palestinian context:

- Aquaponic systems recirculate a volume of water to grow both fish and plants. Water is added only to compensate for evaporative losses and plant growth. In the OPT, access to water is a serious constraint both to agricultural development and to standards of living. Thus, a recirculating system for food production enables maximum use to be extracted from the limited water resources.
- Aquaponic systems are space efficient and can be placed almost anywhere, a significant advantage in the OPT where availability of space for food production is a serious problem, particularly in urban areas and refugee camps. In agricultural areas, land access is being lost through Israeli controls and through effective annexation by the Israeli "Security Fence". The plants have ample nutrition (in the form of fish wastes) and water around their roots at all times, potentially enabling crops to be planted at higher densities, or to give higher yields and grow faster than in traditional agriculture. Nutrient conversion and uptake by the plants maintains good enough water quality to stock fish at fairly high densities, making a viable harvest of food fish possible even in small spaces.
- By producing abundant fresh, organically grown produce, including a high quality protein source (fish), aquaponic systems can help combat malnutrition and food insecurity, and provide new opportunities for income generation in the OPT. At present up to 40% of the population in the OPT (25% in West Bank) are classed as "chronically food insecure" (OCHA 2010), and unemployment stands at around 25% (PCBS 2009).

Objectives of the pilot study

The objectives of this pilot study were to:

1) Construct a pilot domestic scale aquaponic system and evaluate its effectiveness in terms of water and cost efficiency in producing vegetable and fish harvests compared to growing crops in soil.
2) Prepare a training manual and workshop series, to assess the effectiveness as tools for knowledge transfer, and training participants to set up and maintain aquaponic systems independently in the future.

Project activities

The Al-Basma centre had been previously identified as a suitable location for developing this pilot project. The Al-Basma centre caters for young adults with special needs, providing training in a range of different skills and trades. The director of Al-Basma centre is always looking for new and innovative ideas for activities for the clients and for income generation. In addition, the Al-Basma centre has a plastic greenhouse (7m x 15m) on site that has been used for growing cucumbers in the autumns. However, aside from providing activities for the clients, the cucumber project generated a net financial loss for the centre. Thus, the idea of trialling an aquaponic system in the vacant greenhouse appealed greatly to the director and staff of the centre. After consultation with the staff of Al-Basma centre it was obvious that they were enthusiastic about the project and prepared to commit their time to learning about aquaponic systems, and also ultimately prepared to assume responsibility for the project in the long term.

Figure 1: The greenhouse at Al-Basma centre

The project was given the official go-ahead on March 10th 2011. During the following days the required materials were gathered from stores in Beit Sahour and Bethlehem. The greenhouse was cleaned out on March 16th and preparation of materials and construction of the aquaponic system commenced.

The first training workshop “Introduction to aquaponics” was delivered on March 30th to 6 participants, made up of 3 staff from the Al-Basma centre and 3 interested individuals from the community. On April 2nd, a hands-on construction workshop was held, and construction of the aquaponic system was completed. The following day we placed a mesh bag of dry goat manure into the sump tank, and turned on the pumps to allow the system to start cycling to build up the bacterial communities necessary to process fish wastes. Also, soil patches connected to a drip irrigation stem were prepared to mirror each aquaponic grow bed – this was to provide a direct comparison of water usage and plant growth between the soil and aquaponic systems.

Figure 2: Aquaponic system design.
Above: the planned layout of the aquaponic system and soil patches inside the greenhouse.
Below: The finished aquaponic setup - a flood and drain system comprised of 6 separate 1m^2 growbeds, with 900L fish and sump tanks.

On March 23rd and April 9th seeds of a variety of plant species were sown into seedling trays to provide plugs for later transplanting. On April 9th, large seeds (runner beans, butternut squash, melons, watermelons, corn) were sown directly into the aquaponic growbeds and soil patches. On April 20th to 23rd we transplanted seedlings of other plants to the growbeds and soil patches.

Two tanks were prepared for growing duckweed (*Lemna*. Sp.) and *Azolla* sp., small, protein rich, floating plants that make excellent fish food. Under the right conditions, duckweed populations may double in 24 hours. Duckweed and *Azolla* may be fed directly to the fish, or dried or frozen to provide food through the winter months. The duckweed tanks have a surface area of approximately 1m^2 each, and are designed to contain 10-20cm depth of water. A small amount of duckweed and *Azolla* was introduced to each tank, and the water fertilised with a pinch of dry goat manure.

A black soldier fly (BSF) larvae harvester was also constructed. BSF larvae eat any form of organic waste (e.g. kitchen scraps, compost) and grow to a size of about 2cm – making another form of nutritious food for larger fish from nothing but waste. Unfortunately, at time of writing we have still been unable to locate a supplier of BSF larvae in Israel to start the system off, though we do know that the flies are present in some areas.

Figure 3: Duckweed tank (below) and BSF larvae harvester (above)

The first fish were brought on May 4th - 66 tilapia (*O. niloticus x S. galilaeus*) - from Livingreen, an Israeli company which provides aquaponic equipment and training. However, the fish were significantly larger than we had ordered (average 150g rather than 50g), and had already been transported from a different site in the same day meaning that when we went to collect them they were already very stressed. In addition, Livingreen were unable to provide oxygen so we were not able to transport the fish in an ideal manner, i.e. in boxes with sealed bags of water filled up with pure oxygen. Instead we had to improvise with small battery powered air pumps in large (200L) plastic water tanks. To try to reduce transport stress we decided to only bring 66 fish for Al-Basma centre rather than the planned 100. However, on arrival it was clear that the fish had suffered greatly, and we anticipated a high mortality. By May 12th only 7 were still alive.

We started researching other suppliers of tilapia, and eventually came across a fish farmer based north of Nablus in the West Bank. On June 1st we arranged another trip to collect fish, and this time brought 107 tilapia fingerlings of approximately 50g to the Al-Basma centre. This was a much more successful trip, with a total loss of 5 fish from transport stress over the next three days, bringing the total number of fish in the aquaponic system to 109.

On June 13th a shade cloth was put over the greenhouse to reduce the extremely high daytime temperatures inside.

During the whole project proceedings we have continued to monitor operation of the aquaponic system and soil patches, including water consumption, water quality and plant and fish health. The first harvest (basil) was collected and weighed on June 1st. Since then, all other plants have also been harvested. All harvests were taken as they became ready from both the aquaponic system and soil patches. Both the date and weight of harvests was recorded. In addition, weekly photos were taken of each growbed and soil patch to provide a visual record of plant growth.

Throughout the pilot project a series of workshops was delivered to participants (see below), and participants have been encouraged to get involved in the day-to-day operation of the system. For the week commencing June 6th, operation and maintenance tasks were performed by the staff of Al-Basma centre under supervision. From June 16th to July 16th the staff of Al-Basma centre assumed full responsibility for the maintenance and operation of the system. This month enabled us to assess the effectiveness of the training programme, and address any issues discovered.

We conducted a feedback session with the participants to highlight activities which had been performed well and those which had been neglected during their month in charge, and to assess their general impressions of the system and its operation. We also discussed the future of the project. Following this session we constructed an automatic water top-up device for the aquaponic system, and prepared to fully re-plant the system with a selection of marketable crops in line with the wishes of the staff of Al-Basma centre. On August 10th we collected and weighed the last harvests of this pilot project and commenced the re-planting. Also on August 10th we weighed a sample of 55 fish from the fish tank, and re-weighed on August 24th and 31st to be able to ascertain growth rates.

Workshops delivered

March 30: Workshop 1 – Introduction to aquaponics
April 2: Workshop 2 – Construction of aquaponic system
April 6: Workshop 3 – Water quality and monitoring
April 9: Workshop 4 – Fish and plant management
April 20: Workshop 5 – About fish
April 27: Workshop 6 – Fish feeding
May 11: Workshop 7 – Fish health
May 18: Workshop 8 – Plant maintenance session
May 25: Workshop 9 – Plant health
June 1: Stocking fish
June 15: Workshop 10 - Troubleshooting
July 6 – 16: Daily 8am system maintenance practice sessions
July 16: Feedback session

Figure 4: Participants attending a practical workshop session

Results of the pilot project

Food production

The aquaponic system has been operational for 136 days, and fully stocked with fish for 76 days. The amount of food given to the fish has been gradually increased from 60g per day to the maximum rate of 250g per day. This section of the report details the crop production, fish growth, and consumption of inputs by the aquaponics system and the soil patches, and provides an economic comparison of the two systems.

Table 1: Consumption of water, electricity and food by the soil patches and aquaponic system over the 136 days of the pilot project. Costs expressed in ILS (Israeli Shekels).

Input	Aquaponic system	Soil patches
Water		
Total consumption (m^3)	8.81	19.25
Daily consumption (L/day)	64.7	141.5
Unit cost (ILS/m^3)	5	5
Total cost (ILS)	44.04	96.26
Daily cost (ILS)	**0.32**	**0.71**
Electricity		
Total consumption (KWh)	310.08	0
Daily consumption (KWh/day)	2.28	0
Unit cost (ILS/KWh)	0.56	0
Total cost (ILS)	173.64	0
Daily cost (ILS)	**1.28**	**0**
Food		
Total consumption (kg)	12.9	0
Daily consumption (kg/day)	0.25	0
Unit cost (ILS/kg)	8	0
Total cost (ILS)	103.18	0
Daily cost (ILS)	**2**	**0**
Total cost (ILS)	321.36	96.26
Daily running cost (ILS)	**3.6**	**0.71**

As can be seen in table 1, the aquaponic system consumes approximately half as much water as the soil patches. This disparity has remained fairly constant throughout the pilot study, with the ratio of soil water consumption to aquaponic water consumption varying between 1.8:1 and 2.2:1. The aquaponic system uses a small electric pond pump (ATMAN AT-105), consuming 60W, and an air pump (ATMAN HP-4000) consuming 35W. Both pumps are on permanently. Obviously, the soil patches have zero consumption of electricity and fish food. Expressed in financial terms, the aquaponic systems costs about 5 times as much to operate per day than the soil patches; 3.6 ILS (about US$ 1) compared to 0.71 ILS.

Table 2 summarizes the plant productivity of the aquaponic system and soil patches. Detailed comparison tables for each plant type can be found in appendix 1. As can be seen in table 2, the aquaponic system was far more productive during this pilot study, with an economic production potential almost 4.5 times greater than the soil patches; 8.53 ILS/day compared to just 1.91 ILS/day. This is before taking into account any production of fish.

Table 2: Daily production of the aquaponic system and soil patches during the pilot study. Production is shown in grams per day per plant, total grams per crop and total value at current market prices in Israeli Shekels.

	Number of plants	Value (ILS/kg)	**Aquaponic daily production**			**Soil daily production**		
			g/plant	g (total)	Value (ILS)	g/plant	g (total)	Value (ILS)
Basil	6	167	5.02	30.12	5.03	1.66	9.96	1.66
Mangold/chard	12	20	5.83	69.96	1.4	NA		
Tomato	6	4	35.6	213.6	0.85	8.3	49.8	0.19
Okra	2	17	14.88	29.76	0.51	1.19	1.19	0.02
Sweet pepper	4	4	7.82	31.28	0.13	1.06	4.24	0.017
Chilli pepper	4	5	0.33	1.32	0.007	NA		
Butternut squash	4	7	18.64	74.56	0.52	0.43	1.72	0.01
Melon	4	3.5	6.1	24.4	0.09	NA		
Total (ILS/day)					**8.53**			**1.91**

Some additional crops were sown that are not listed in the table 2; namely aubergine, maize, peas, lettuce, spinach, rocket and runner beans. For the most part, the reason these plants have not been included is that they failed to establish in either system – a result of being planted at the height of summer in a greenhouse. These crops would be better suited to growing throughout the autumn and winter. Maize grew very well in the soil patches, but initially did not do well at all in the aquaponic system. Once the pH of the aquaponic system had been brought to an acceptable range (6.8-7.5) the maize started to recover. However, we failed to harvest any acceptable corncobs from either system, most probably a consequence of having planted the maize sparsely in rows, and thus failing to achieve a good pollination rate. The aubergine plants appeared much stronger in the aquaponic system than in the soil patches, and indeed two fruits were harvested from the aquaponic system, but unfortunately no information was recorded about this harvest.

Fish growth in the aquaponic system (table 3) was not monitored for the first two months after stocking; we commenced weighing fish once the feed rate had been gradually increased up to the optimal rate for the system (250g/day). The fish were weighed on the 10th, 24th and 31st August; regular weighing will continue for the next few months.

Unfortunately, during fish weighing it came to light tat 20 fish had disappeared. No mortalities had been recorded since June, and so the number of fish was assumed to be 109. However, at the weigh in we captured all the fish and found only 89. We can only presume that the missing fish were stolen from the system by children that had been breaking in to the Al-Basma centre in July and August.

Table 3: Growth of fish in the aquaponic system between 10th August 2011 and 24th August 2011

Date	Sample size	Mean ± s.d. Weight (g)	Total weight (89 fish) (kg)	Growth (g) per day Total	Growth (g) per day Per fish	Value (ILS/kg)	Total daily production (ILS)
10/8/11	57	109.6 ± 45.4	9.754				
31/8/11	89	157.1 ± 48.85	13.980	201	2.26	50	10.07

As shown in table 3, the mean fish weight had increased over the course of two weeks. The variation in weights of individual fish was found to be large, ranging from 80g to 315g on the 31st August, but nevertheless the increase in mean weights between the two sampling dates was found to be statistically significant by a two sample T-test (T-value = -5.89; d.f. = 144; $P < 0.001$).

The fish are being fed a total of 250g pellet food every day in two servings of 125g; morning and evening. This equates to 2.81g food per fish per day. The observed growth of the fish is 2.26g per fish per day. This gives a Food Conversion Ratio (FCR: weight of food given ÷ weight gain) of 1.24

Figure 5: A healthy tilapia from the aquaponic system

Although we intended to stock only male tilapia, it would appear that we also have some females in the fish tank. Each time that we have netted fish to weigh them, we have also ended up netting approximately 100 young fry. We relocated the fry to duckweed tanks where they can grow on a natural diet of zoo and phytoplankton. After almost three weeks the first batch of fry transferred have grown noticeably.

Figure 6: Mangold (Swiss chard) in aquaponic system (left) and soil (right). Plants transplanted on May 3rd, photo taken June 12th.

Figure 7: Plant growth comparison photos of soil patches 1-3 (right), growbeds 1-3 (right centre), growbeds 4-6 (left centre) and soil patches 4-6 (left).
Photos were taken on April 10th (top), May 7th, May 18th and June 12th (bottom).

Figure 8: Details of plants in the aquaponic system (left column) and soil patches (right column). From top to bottom:

Aubergine: Plants transplanted on May 23rd; photo taken June 12th.

Maize: Seeds sown direct on April 9th; photo taken June 12th.

Butternut squash: Seeds sown direct April 9th; photo taken June 12th.

Okra: Seeds sown direct April 9th; photo taken August 10th.

Plant health

There is no way to formally quantify plant health, but it has been apparent during the course of the pilot project that the aquaponic system encourages healthy plants. Initially, while the pH was high, most plants in the aquaponic system displayed symptoms of nutrient deficiency (stunted growth, yellowing leaves). Once the pH in the aquaponic system was brought under control, plant health improved visibly. Not only did signs of nutrient deficiency disappear, growth rate increased dramatically.

Plants in both the aquaponic system and soil patches have been affected by spider mite, aphids and whitefly. The spider mite infestation was largely controlled by deploying predatory mites. After that we started spraying molasses once to twice a week (a dilution of 1 teaspoon per litre) as a foliar feed. Since the pilot is in a green house, we have brought and encourage beneficial insects like ladybirds and bees to aid pollination and control pests.

The whole greenhouse has been plagued by whitefly; some plants, the okra in particular, are heavily infested. We are trying to control the infestation using sticky yellow fly traps and regular foliar sprays of garlic water or molasses solution. The infestation remains, but all plants are still showing good growth rates and fruit production.

Overall it has been evident that the plants in the aquaponics system are more resilient and recuperate from pest attack faster than the plants in the soil.

Knowledge transfer

We have delivered the planned series of workshops (see “Project Activities”, above) and encouraged participants to get involved in the project. Despite initial reticence to take over the full responsibility of managing the aquaponic system (citing concerns over time requirement, difficulty level of necessary activities, preference to not touch fish…), the staff of Al-Bamsa centre took complete control for the period of one month from mid-June to mid-July. During this time they received no assistance or supervision. Feedback and observations after this month enabled us to assess the effectiveness of the training programme.

We found that in general the system had been well maintained: pH had been kept under control; fish had been fed the correct amount and on-time; water quality had been monitored, and when a problem was noticed then feed rate was reduced appropriately. In addition, crops had been harvested as they became ready, and the pump was replaced when it broke down.

There were, however, a few problems. Probably the most significant was the failure to top up the water level in the aquaponic system often enough. As water is consumed by plants and lost by evaporation, the water level drops. If it drops too much the pump becomes exposed, and therefore ceases to function. This causes problems for the fish and the plants, and shortens the lifespan of the pump.

We also noted a problem with plant management; for example, the tomatoes had not their suckers removed, resulting in an unmanageable tangle of growth. Some of the basil had been allowed to flower, resulting in a slowdown of leaf production and a bitter flavour in the leaves.

A final issue we observed was that not all the harvests had been recorded adequately. This is not a problem as far as maintaining the system goes, but it has made data analysis for this study more complex.

On-site fish food and fingerling production

At present, fish are being fed manufactured pellet feed at the optimal rate for the system 250g per day. This is based on the filtration capacity of the growbeds, and equates to a feed rate of approximately 1.6% body mass per day.

We have been successfully growing both duckweed (*Lemna* sp.) and *Azolla* sp., but have not yet switched over to feeding the fish from this source. The reason for this is that using the manufactured feed enables us to accurately calculate food rations and food conversion efficiency, and thus compare the production efficiency of this aquaponic system with other aquaculture facilities around the world.

We have, however, found an alternative interim use for the duckweed tanks – fry rearing. The two batches of juvenile tilapia collected during fish weighing have been transferred to the duckweed tanks. There they are able to feed on the a whole range of natural foodstuffs, from duckweed to phytoplankton, mosquito larvae and water fleas (*Daphnia* sp.). The fry have already grown visibly.

Figure 9: Tilapia fry collected from the aquaponic system

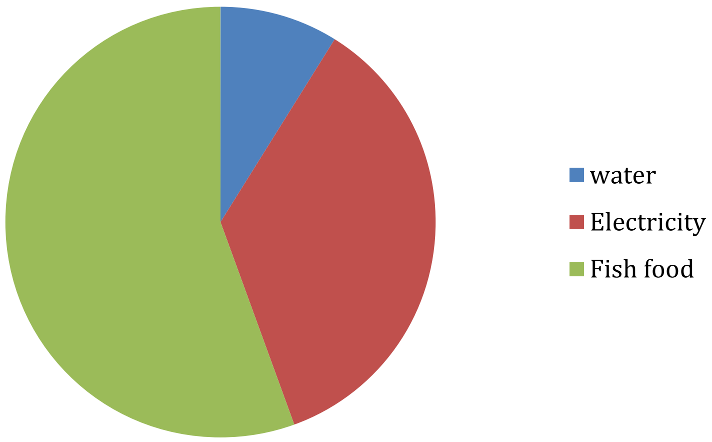
Project budget

Despite some unanticipated expenses early on, the pilot project has remained very close to the original proposed budget. This has been in part due to some of the participants being able to translate for us during workshops, saving the expense of a translator. Significant additional expenditure has however been made on the shade cloth for the greenhouse (600 ILS) and on the second trip to collect fish (360 ILS). In addition, the time requirement for constructing, training and maintaining the system was underestimated in the original budget; the actual requirement was 419 hours, and not the 264 originally estimated.

Discussion

This pilot study has demonstrated that an aquaponic system can be a very resource efficient means of food production. In the OPT water availability is a very serious constraint to development in the domestic scale or commercial agriculture sectors. In this study we found that the aquaponic system used approximately half the water of the soil patches, while producing a higher agricultural yield. The aquaponic system did, however, require other inputs in addition to water; namely electricity and fish food. In a breakdown of costs it was found that the daily input requirement of the aquaponic system was 3.6 ILS, compared to 0.71 ILS in the soil patches. As can be seen in chart 1, the highest contributor to the running cost of the aquaponic system was the fish food.

Chart 1: Breakdown of the daily running costs of the aquaponic system.



We still hope to be able to reduce the need for purchased fish food in the long term; we are successfully growing the aquatic plants duckweed (*Lemna* sp.) and *Azolla* sp. and intend to start incorporating them into the diet on a regular basis. However, at present it is still useful to use the manufactured feed as it is very easy to measure the amount being given and thus calculate the food conversion ratio (FCR) of the system. We are also still trying to locate a source of black soldier fly (*Hermetia ilucens*) larvae so that we can establish a colony to produce nutritious, live fish food from kitchen scraps.

Since we commenced regular weighing of the fish, we have found the FCR to be 1.24. This is lower than the industry standard FCR of 1.5 - 2 for intensively reared tilapia[1], and demonstrates a more efficient usage of feed than in most recirculating aquaculture systems. This is probably because the aquaponic system is in fact an ecosystem, and uneaten food and fish wastes are not removed from the system, but taken up by microbes and other organisms which may then be eaten by the fish.

[1] Stickney, R. 2009. *Aquaculture: an introductory text*. 2nd ed. **CABI**, London. ISBN-13: 978-1-84593-543-6

The crop output from the aquaponic system was found to exceed that of the soil patches, both in weight and frequency of harvests. Calculated in economic terms, during this pilot study the soil patches were generating a gross financial potential of 1.91 ILS/day compared to 8.53 ILS/day in the aquaponic system. If we factor in the growth of the fish, and subtract the cost of the inputs, the daily income generation potential of the aquaponic system was found to be 15ILS compared to just 1.2ILS from the soil patches.

We have yet to collect a harvest since re-planting the aquaponic system with the crops selected by the staff of Al-Basma centre. However, based on the plant performances from the pilot study we can partially project a crop/income yield. Table 4 shows the projected yield of four of the crops in the new system layout. The other crops planted (mint, parsley, rocket, spinach, chives, broccoli, cauliflower and lettuces) have not been included in table 4 as we do not know how they will perform because we have not yet trialled them in an aquaponic system. We expect that rocket and spinach will show similar production to the chard. By focussing on fairly high value crops with good production rates we hope to be able to increase the overall profitability of the system.

Table 4: Projected yield of four crops following the re-planting of the Al-Basma aquaponic system on August 16th 2011.

			Daily production		
Crop	Number	Value (ILS/kg)	Per plant (g)	Total (g)	ILS
Basil	19	167	5.02	95.38	15.93
Chard	11	20	5.83	64.13	1.28
Pepper	9	5	7.82	70.38	0.35
Chilli	12	6	0.33	3.96	0.024
Total					**17.58**

Assuming the aquaponic system can be maintained at the production rate projected in table 4, with fish growth continuing as at present, then daily net production would be 24.05 ILS; 31% and 52% of the average daily salary in the West Bank and Gaza respectively (PCBS 2011 – daily salaries in the West Bank: 76.9 ILS; Gaza 46.2 ILS). Even by maintaining the production rate of the pilot study, a similar aquaponic system could generate the equivalent of 19.5% (West Bank) or 32.5% (Gaza) of the median daily salary.

Challenges encountered and recommendations

During the course of this pilot study we have encountered a range of different challenges. This has forced us to think about many aspects of the project, with the ultimate benefit of having learnt much more in divining solutions to the problems than we would have done had everything run “perfectly” from day one. The main lessons learnt are summarised below.

We observed that the most problematic areas of the aquaponic system operation were regular topping up with fresh water, and management of complex plants such as tomatoes.

To avoid problems with topping up we have now automated the process by installing a ball valve in the sump tank that can deliver fresh water as and when it is needed. We would recommend that this become a standard part of system construction in any future projects.

To reduce problems with plant management we would recommend growing easier plants – at least initially – unless the participants have prior experience growing more complex plants and/or have sufficient time to commit to maintaining them properly.

All pipework should be as wide-bore and straight as possible, to reduce resistance and allow high water flow rates. In this system, 50mm pipe leading to four 32mm pipes are used to draw water and fish wastes from the fish tank to the growbeds. On the same theme, it is important to keep the pipework clean inside. After some time running, a biofilm can develop inside the pipes which can seriously reduce flow rates. This then has a knock on effect on the functioning of the siphons and could ultimately lead to serious problems for the fish and plants. Thankfully, it is a relatively quick and easy job to clean out the pipes.

If possible, use only rainwater for the system. In the OPT most of the water supply is groundwater, which has a high pH (up to 8.4) and high alkalinity (up to 200ppm $CaCO_3$), whereas rainwater has a pH much closer to 7. Aquaponic systems work best with a pH of 6.8 - 7.5, and so if groundwater is to be used, the pH must be brought down. This is fairly easy to achieve by adding acid to first neutralise the alkalinity, and then to reduce the pH. However, if fish are already in the system, the acid must be added very gradually to avoid pH swings. It is preferable to add acid to the water before the water goes into the aquaponic system – for example by filling a barrel with water and adding the right quantity of acid, leaving it for 24 hours and re-checking the pH, then putting it into the system. Phosphoric acid, H_3PO_4, is readily available in garden centres and not only reduces pH but also adds phosphate (an essential plant nutrient) to the system. We have successfully used phosphoric acid to lower the pH, adding 18ml per day to the aquaponic system to bring the pH from 8.5 on May 7th to 7.47 on June 1st. Now the system is running at an optimum pH of 6.8-7.

Light should be kept out of the water in aquaponic systems to prevent plankton blooms. This means either using opaque materials, or shading the fish and sump tanks' walls and tops, shading the sides of the growbeds, and ensuring that there is always a few centimetres of gravel on top of the maximum water level in the growbeds. If a plankton bloom does occur, the plankton will out-compete the plants for nutrients, causing them to stop growing. Plankton will also consume dissolved oxygen leading to problems for the fish. When the plankton dies, it will suddenly re-release a lot of nutrients to the water, which could result in an ammonia or nitrite spike.

It is important to transport fish appropriately, which is facilitated by acquiring them from a reputable source. If in doubt, then double check the availability of oxygen, the size of the fish, and whether they will come direct from the supplier, or if the supplier is acting as a middle-man. We located a supplier of fish in the northern West Bank, that is able to provide tilapia and carp, which opens up fish acquisition to all West Bank Palestinians. Bringing fish from Israeli suppliers obviously presents its own logistical challenges. This supplier does not run a commercial hatchery, and as such does not necessarily always have fish – it is worth contacting him in advance to enquire. He also does not have oxygen on site. However, we were able to borrow a cylinder from the Civil Defence, and have it filled with oxygen in a hospital.

Over winter, aquaponics systems must be kept warm (not lower than 15°C for the bacteria in the growbeds to remain active). It is therefore beneficial to place the system inside a greenhouse. However, in the summer temperatures inside a greenhouse will get very high, causing problems for some of the plants and increasing the rate of evaporative water loss from the system. Covering the greenhouse with a shade cloth can help keep inside temperatures down. The best solution of all, however, would be to place the system under a frame that can be covered with plastic in the winter, and shade in the summer.

We have found that plants can grow very vigorously in the aquaponic system, and attain a large size. It is therefore very important to consider this when planting the growbeds. A fast-growing, large leafed plant will quickly shade anything planted too close. The plant in the shade will then not flourish. It is possible to relocate plants in gravel growbeds, but obviously better to plant them in the correct place to start with.

Large seeds can be sown direct into the growbed. However, it is best to avoid planting them too close to the inlet pipe, as being continually wet will lead to rot. Some smaller seeded plants (e.g. coriander) do not transplant well, but the seeds are too small to sow direct. A good solution is to put a layer of wool/cotton at the desired planting depth, place the small seeds on top and finally place the gravel gently on top of the seeds. In this way, small seeds will not be washed away by the tidal action of the growbed.

Human interference (accidental or otherwise) with the aquaponic system can cause problems. For example, eager visitors leaning on the pipes to try to look at the fish, or playing with the siphon assembly can alter their performance or even cause breakages and leaks. Also, careless movement around the system can cause damage to the plants. It is important therefore to supervise visitors, and to explain what (and why) they should avoid doing. A daily visual check to ensure that all the growbeds are filling and draining properly, and that the pump and aerator are running, also helps to detect problems before they become serious.

Another problem posed by unsupervised visitors is the risk of theft. Strangely none of the more valuable pieces of equipment (pump, aerator) went missing, which suggests that the theft was not financially motivated. Most likely the fact that live fish are such a novelty in the West Bank led to their disappearance. To prevent future thefts it would be advisable to lock the greenhouse, or even lock the lid onto the fish tank.

Conclusion

This pilot project has demonstrated a good case for aquaponics as a resource efficient means of food production in the OPT. The aquaponic system uses water more efficiently than conventional agriculture, and uses fish food more efficiently than conventional aquaculture. In addition, both the plant and fish production aspects of the aquaponic system showed significant harvests and growth during this pilot study.

From an economic viewpoint, it has been shown that an aquaponic system could contribute significantly to household incomes. Given the high unemployment in some areas of the OPT (17.2% in the West Bank, 37.8% in Gaza and reaching highs of 80% in some refugee camps – PCBS 2011), then an aquaponic system requiring no more than 10-30 minutes of attention each day - yet able to contribute up to upwards of 30% of the average daily salary – could become a very effective tool in helping lift families out of poverty. Alternatively, an aquaponic system could provide a range of fresh, organically grown vegetables and fish to families least able to afford such high quality food.

In terms of knowledge transfer, and peoples' interest and willingness to try aquaponics we have found the pilot project to be very encouraging. The project participants have all learned a lot. None of the participants had any agricultural or aquaculture background, and they expressed concerns that the material presented could be too difficult as they could barley remember basic high school science. Now they are in a position to be able to take over managing the system full time. In addition the project has attracted a lot of interest in the community, with a number of individuals and NGOs expressing the desire to construct their own aquaponic systems for domestic use or for food security/income generation projects.

Figure 10: The thriving aquaponic system at the Al-Basma centre

Appendix 1: Plant production by crop

For each harvest, the date and weight from each plant was recorded. In the case of fruit harvests, then both the weight and number of fruits were recorded. The tables below detail the production of each crop.

Unfortunately, in some instances fruit harvests were only recorded as a total weight or number of pieces. For the purposes of analysis, the missing data was extrapolated by multiplying the number of fruits (or dividing the total weight) by the overall mean weight per fruit from all harvests in which both weight and number were recorded.

The average yield per harvest was calculated by dividing the total weight harvest by the number of harvests.

The average growth per day was calculated by dividing the average yield per harvest by the average number of days between harvests.

Basil

	Aquaponic	**Soil**
Number of plants	6	6
Date transplanted	23 April	23 April
Date of first harvest	01 June	01 June
Growth period to first harvest	39 days	39 days
Yield – total weight	1,952g	645g
Average time between harvests	10.8 days	10.8 days
Average yield per harvest	325.3	107.5
Average growth per day	30.12g	9.95g
Average growth per plant per day	5.02g	1.66g

Mangold (Swiss chard)

	Aquaponic		**Soil**	
Number of plants	6	6	6	6
Date transplanted	11 May	9 June	11 May	9 June
Date of first harvest	18 June	4 August	NA	NA
Growth period to first harvest	38 days	56 days	No harvest to date	No harvest to date
Yield – total weight	2,244g	312g	0g	0g
Average time between harvests	10.6 days	3 days	NA	NA
Average yield per harvest	374g	104g	NA	NA
Average growth per day	34.7g	35.2g	NA	NA
Average growth per plant per day	5.88g	5.78g	NA	NA

Tomato

	Aquaponic	Soil
Number of plants	6	6
Date transplanted	20 April	20 April
Date of `harvest	09 July – 10 August	09 July – 10 August
Growth period to first harvest	80 days	80 days
Yield – total weight	7,590g	1,874g
Yield – number of fruit	140	56
Average time between harvests	3.6 days	5.3 days
Average yield per harvest	759g (14 fruit)	267g (8 fruit)
Average fruit growth per day	213.5g	50.2g
Average fruit growth per plant per day	35.6g	8.3g

Butternut squash

	Aquaponic	Soil
Number of plants	4	4
Date sown	9 April	9 April
Date harvested	16 July	16 July
Growth period from seed	98 days	98 days
Yield – number of fruit	14	1
Yield – total weight	7,307g	171g
Average fruit growth per day	74.6g	1.74g
Average fruit growth per plant per day	18.64g	0.43g

Melon

<table>
<tr><th></th><th colspan="2">Aquaponic</th><th>Soil</th></tr>
<tr><td>Number of plants</td><td colspan="2">4</td><td>4</td></tr>
<tr><td>Date sown</td><td colspan="2">9 April</td><td>9 April</td></tr>
<tr><td>Date harvested</td><td>13 July</td><td>5 August</td><td>Never</td></tr>
<tr><td>Growth period from seed</td><td>95 days</td><td>118 days</td><td>118 days</td></tr>
<tr><td>Yield – number of fruit</td><td>2</td><td>2</td><td>0</td></tr>
<tr><td>Yield – total weight</td><td>2,783g</td><td>2,300g</td><td>0g</td></tr>
<tr><td>Average fruit growth per day</td><td colspan="2">24.4g</td><td>NA</td></tr>
<tr><td>Average fruit growth per plant per day</td><td colspan="2">6.1g</td><td>NA</td></tr>
</table>

Okra

	Aquaponic	Soil
Number of plants	2	1
Date planted	9 April	9 April
Date of first harvest	28 July	13 June
Growth period to first harvest	110 days	126 days
Yield – total weight	561g	31g
Yield – number of fruit	29	4
Average time between harvests	4.7 days	6.5 days
Average yield per harvest	70.13g (3.6 fruit)	7.75g (1 fruit)
Average fruit growth per day	14.88g	1.19g
Average fruit growth per plant per day	7.44g	1.19g

Sweet pepper

	Aquaponic	Soil
Number of plants	4	4
Date transplanted	23 April	23 April
Date of first harvest	26 June	26 June
Growth period to first harvest	64 days	64 days
Yield – total weight	1,463g	165g
Yield – number of fruit	25	3
Average time between harvests	7.8 days	1 harvest only
Average yield per harvest	244g (4 fruit)	165g (3 fruit)
Average fruit growth per day	31.3g	4.2g
Average fruit growth per plant per day	7.82g	1.06g

Chilli pepper

	Aquaponic	Soil
Number of plants	4	4
Date transplanted	23 April	23 April
Date of first harvest	25 June	No harvest to date
Growth period to first harvest	63 days	NA
Yield – total weight	91g	0g
Yield – number of fruit	18	0
Average time between harvests	17.3 days	NA
Average yield per harvest	22.75g (4.5 fruit)	NA
Average fruit growth per day	1.3g	NA
Average fruit growth per plant per day	0.33 g	NA

Appendix 2: Project budget

	Description of activity/item	Quantity	Total (ILS)
1.1	**Project Staff**		**21,886**
	Technical support @ US$18.75/hour	264 hrs	17,886
	Translation of written material @ 50 ILS/page	Per page (X 80)	4,000
1.2	**Training Material**		**2,750**
	Printing workshop booklet material	X 20	
	Printing posters	X 5	
	Printing recipe book	X 20	
1.3	**Construction of Pilot Aquaponic System**		**7,085**
	Materials, tools, plumbing, water testing (see annex 1)	1	6,977
1.4	**Stocking and running costs**		**3,391**
	Fish	100	847
	Battery pumps	3	153
	Batteries	8	112
	Fish feed	1 sack	200
	Plant seeds	10 packets	53
	Plants seedlings	62	186
	Predatory mites (organic pest control)	2 bottles	120
	Seedling tray	3	30
	Compost	2 bags	30
	Transport	2 day car hire, fuel	1,660
	Running cost (electricity, water)	Pay by system host	0
Total			**ILS 35,112**

Appendix 3: Itemised parts list for aquaponic system setup

Part	Quantity	Unit	Unit price	Total
Structure				**3,076**
Breeze blocks	60	Item	2.1	126
Pallets	8	Item	12	96
Shade cloth	16	M^2	6	96
White tanks (IBC, $1m^3$)	7	Item	150	1,050
Volcanic rock	3	m^3	500	1,500
Blue barrels	3	Item	27	80
Electrics (30m extension lead) plugs and sockets	1	Item	128	128
Plumbing				**1,654**
Pump	1	Item	150	150
Aerator	1	Item	255	255
Air stones	4	Item	4	16
Air line	8	m	3	24
Pipe 3", 50cm pieces	6	Item	11	66
Cap and grommet for 3" pipe	6	Item	4	24
Pipe 4"	2	m	10	20
¾" thread male to male adaptor	7	Item	4	28
1" thread to 25mm pipe nipple	6	Item	4	24
25mm pipe clamp L	6	Item	10	60
PVC tap 2"	1	Item	34	35
PVC tap ¾"	7	Item	10	70
PVC T 50mm	4	Item	10	40
L 2" thread	1	Item	10	10
PVC L 32mm	4	Item	8	32
PVC T 32mm	2	Item	8	16
T 25mm pipe clamp, 1" thread	1	Item	10	10
PVC pipe 32mm	10	m	8	80
PVC pipe 50mm	3.5	m	10	35
PVC pipe reducer 50 – 32mm	10	Item	6	60
PVC adapter 32mm - 1" thread	6	Item	7	42
PVC adapter 32mm – ¾" thread	6	Item	7	42
T 50 mm threaded	1	Item	15	15
PVC adaptor 2"/50mmm	4	Item	10	40
Reducer threaded 2" male – 1" female	1	Item	10	10
Wall connector 2"	2	Item	10	20
Pipe 25mm	12	m	2	24
Hose tap connector	1	Item	5	5
Hose pipe	20	m	3	60
Water meters and connectors	2	Item	160.5	321
PVC solvent cement	1	Item	20	20
Tools				**1,065**
Angle grinder	1	Item	400	400
Angle grinder scrubs	3	Items	9	27

Metal cutting disc	6	Item	4	24
Drill	1	Item	300	300
Drill bits: 1", 8mm, 6.5mm, 4mm	4	Item	16	62
Wood saw	1	Item	1	20
Hacksaw	1	Item	10	10
Sealant	1	Item	22	22
Sealant gun	1	Item	15	15
Thinner	2	Litre	21	42
Nuts and bolts	50	Item	0.84	42
Safety goggles	3	Item	10	30
Gloves	2	Item	10	20
Scrubbers	2	Items	12.5	25
Nails, scraper and key	1	Item	26	26
Water Testing				**920**
Ammonia test kit	1	Item	80	80
pH meter	1	Item	400	400
Nitrate test kit	1	Item	80	80
Nitrite test kit	1	Item	80	80
EC meter	1	Item	200	200
Hardness test kit	1	Item	80	80
Harvesting tools				**40**
Secateurs	1	Item	20	20
Net	1	Item	20	20
Delivery of materials				**330**
Total ILS				**7, 085**