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Food Production and Water Conservation in a Recirculating Aquaponic System in Saudi Arabia at Different Ratios of Fish Feed to Plants

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Abstract

An indoor aquaponic system (i.e., the integration of fish culture with hydroponic plant production in a recirculating setup) was operated for maximizing water reuse and year-round intensive food production (Nile tilapia, *Oreochromis niloticus*, and leaf lettuce) at different fish feed to plants ratios. The system consisted of a fish culture component, solid removal component, and hydroponic component comprising six long channels with floating styrofoam rafts for holding plants. Fish culture effluents flowed by gravity from the fish culture component to the solid removal component and then to the hydroponic component. Effluents were collected in a sump from which a 1-horsepower in-line pump recirculated the water back to the fish culture tanks at a rate of about 250 L/min. The hydroponic component performed as biofilter and effectively managed the water quality. Fish production was staggered to harvest one of the four fish tanks at regular intervals when fish attained a minimum weight of 250 g. Out of the total eight harvests in 13 mo, net fish production per harvest averaged 33.5 kg/m^3 of water with an overall water consumption of 320 L/kg of fish produced along with the production of leaf lettuce at 42 heads/m^2 of hydroponic surface area. Only 1.4% of the total system water was added daily to compensate the evaporation and transpiration losses. A ratio of 56 g fish feed/m^2 of hydroponic surface effectively controlled nutrient buildup in the effluents. However, plant density could be decreased from 42 to 25–30 plants/m^2 to produce a better quality lettuce.

Freshwater is an expensive commodity in Saudi Arabia because of limited sources and adverse climatic conditions. Thus, despite an increasing demand for fresh fish, the development of freshwater aquaculture here is slow, and its further expansion now depends upon the application of new technologies to intensify fish culture and to maximize water reuse (Al-Hafedh et al. 2003; Al-Hafedh and Alam 2005). Aquaponics is a biointegrated food production system that links recirculating aquaculture with hydroponic vegetable, flower, and/or herb production (Diver 2006). It is a very productive and ecologically sound food production system, where fish waste provides a nutrient source for nitrifying bacteria, which in turn convert toxic waste of the fish to useful nutrients for plants. Mineralized solid waste is also used for the plants' benefit. Thus, plants associated with nitrifying bacteria provide a natural filter to eliminate toxic waste of the fish. This creates a mini ecosystem where both plants and fish can thrive. It further maximizes production and uses less water than is used to produce the same quantity of fish and vegetables in traditional practices.

Although the practices of fish farming and hydroponics have been traced to ancient times, the combination of the two is quite new. Research in aquaponics began in the 1970s, and the integration of aquaculture and the hydroponic cultivation of plants has been examined repeatedly over the past three decades with a wide variety of system designs, plant and aquatic animal species, and experimental protocols (Rakocy and Hargreaves 1993). Until the 1980s, most attempts at integrated hydroponics and aquaculture had limited success; however, innovations since the 1980s have transformed aquaponics technology into a viable system of food production (Diver 2006). McMurtry et al. (1993, 1997) created the first-known closed-loop aquaponic system (called an aqua-vegeculture system) in 1986 that channeled tilapia effluent into sand-planted tomato beds.

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Commercially, aquaponics is in its infancy, but as the technology develops and is refined, it has the potential to be a more efficient and space-saving method of growing fish, vegetables, and herbs. The essential elements of aquaponic system consist of a fish rearing tank, a suspended solid removal component, a biofilter, a hydroponic component, and a sump (Rakocy and Hargreaves 1993).

Different types of hydroponic media have been used for growing crops in freshwater aquaponic systems, including gravel bed ebb and flow systems, aeroponics, nutrient film technique (NFT), rock wool culture, and sand beds (Gonzales 2002). McMurtry et al. (1990) used sand as a medium for growing vegetables using aquaculture effluents, whereas floating polystyrene rafts were used by Rakocy and Nair (1987). Lennard and Leonard (2006) have compared gravel beds, NFT, and floating rafts to grow lettuce in aquaponics. According to Rakocy (1995), raft hydroponics, which consists of floating sheets of polystyrene for plant support, can also provide sufficient biofiltration if the plant production area is sized properly. Thus, combining biofiltration with hydroponics is a desirable goal, and eliminating the expense of a separate biofilter is one of its main advantages.

Aquaponics recycles water and nutrients that would otherwise be discharged into the environment, possibly causing pollution. Aquaponic systems work by balancing nutrient generation from fish waste with nutrient uptake by plants to achieve proper water quality. Plants perform as a biofilter, purify effluents, extend water reuse, and eliminate the need for a separate biofilter. Aquaculture effluent provides most of the nutrients required by plants if the optimum ratio between daily feed input and plant growing area is maintained (Rakocy et al. 2004). Vegetables recover a large portion of the dissolved nutrients originating from fish waste and are produced as a secondary crop to improve the systems profit potential at the commercial level. Adler et al. (2000) have also concluded that the hydroponic system drives potential profitability of the combined system with major annual returns deriving from plant production. No pesticides or antibiotics are used at any stage; therefore, the aquaponic production system can be regarded as a part of the organic agriculture (Rakocy 1999).

More than 30 types of vegetables have been raised in integrated systems on an experimental basis (Rakocy et al. 1992). Lettuce, herbs, and specialty greens (spinach, chives, basil, and watercress) have low to medium nutritional requirements and are well adapted to aquaponic systems, whereas fruiting plants (tomatoes, bell peppers, and cucumbers) have a higher nutritional demand and perform better in a heavily stocked, well-established aquaponic system (Diver 1996).

Various fish species are presently used in aquaponic systems including Nile tilapia, *Oreochromis niloticus*; hybrid tilapia, *Oreochromis urolepis hornorum* × *Oreochromis mosambicus*; koi carp, *Cyprinus carpio*; hybrid carp, *Ctenopharyngodon idella* × *Aristichthys nobilis*; hybrid striped bass, *Morone chrysops* × *Morone saxatilis*; and goldfish, *Carassius* sp. (Selock 2003). Rainbow trout, *Oncorhynchus mykiss* (Adler et al. 2000); Australian barramundi, *Lates calcarifer*; and Murray cod, *Maccullochella peelii peelii*, as well as various crustaceans such as red claw crayfish, *Cherax quadricarinatus*, have also been grown in aquaponic systems (Diver 2006).

Generally, recirculating aquaculture systems require continuous wastewater treatment using a variety of techniques that have traditionally been relatively expensive and require very skillful personnel to operate (Losordo et al. 1992). The design of the water reuse system, thus, needs to be efficient, cost effective, and simple to operate. Establishment and testing of recirculating aquaculture technologies, including aquaponics, using local resources under specific climatic and culture conditions, therefore, is one of the most significant approaches for maximizing water reuse and increasing food production in Saudi Arabia.

The main objectives of this research include the operation of an aquaponic system for producing marketable fish and vegetables throughout the year, to achieve intensive tilapia production at more than 80 kg/m^3/yr (2 crops/yr) and up to 42 lettuce heads/m^2/mo, and to observe the effects of varying plant to fish feed ratios on the system performance. The system was operated using groundwater with an ambient total dissolved solid (TDS) contents from 1.2 to 1.5 ppt compared to the other aquaponic systems that were operated using collected rainwater (Rakocy and Hargreaves 1993; Rakocy et al. 1997).

Materials and Methods

System Design

The aquaponic system was installed as per the design of a commercially viable aquaponic system developed for the resource-limited tropics by Dr. James Rakocy and his associates at the University of Virgin Islands, St. Croix, Virgin Islands, USA (Rakocy 1999). The system consists of three basic components: fish culture component, solid removal component, and hydroponic plant growing component for biofiltration (Fig. 1). All fish culture tanks, filter tanks, and the sump were constructed from fiberglass (SKAFCO, Riyadh, Saudi Arabia), while the aquaponic channels constructed of concrete blocks lined with high-density, 5-mm-thick polyethylene liner.

The fish culture component consisted of four circular fish rearing tanks (total volume 9.5 m^3 and water volume 7.5 m^3 each). The solid removal component consisted of two cone-bottomed cylindrical clarifiers (total volume 4 m^3 each) and four rectangular filter tanks (total volume 0.85 m^3 each) containing nylon bird netting. A rectangular tank (total volume 0.85 m^3) was used for degassing. The hydroponic component consisted of six channels (29.6 × 1.2 × 0.4 m each, total 213 m^2 surface area) for growing plants and performing as biological filters. The degassing tank contained 10 air diffusers (15.2 × 3.8 × 3.8 cm) and three standpipes (10 cm diameter each). Standpipes distributed the effluent to three pairs of hydroponic channels. Each fish rearing tank and the aquaponic channel were aerated by 22 (15.2 × 3.8 × 3.8 cm) and 24 (7.6 × 2.5 × 2.5 cm) air diffusers, respectively. A circular sump (total volume 1 m^3) collected return water from the hydroponic component. The purified water was then pumped back to fish culture component. Fish rearing tanks had a 3% slope toward a central bottom drain to enhance the solid removal. The drain lines from the apex of the clarifier cone projected above the ground. A valve on the drain line was opened to collect the sludge. Aquaponic channels contained standpipes to maintain the desired water level (33 cm). Each channel contained 48 styrofoam rafts (each measuring 120 × 60 × 5 cm). A 1/2-horsepower pump was installed near the sump tank to pump the water from the sump to fish rearing tanks.

Operation

Water flowed by gravity from the central bottom drain of the fish rearing tanks to the cone clarifiers and then through net filter and

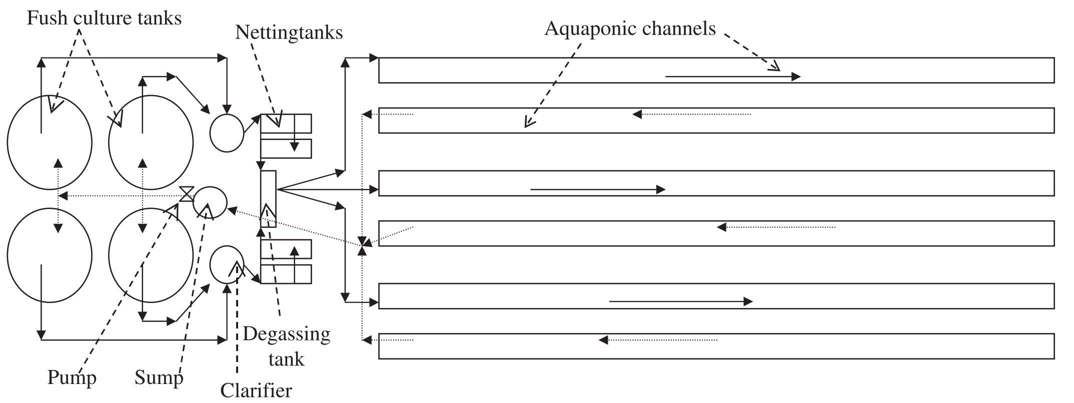

FIGURE 1. *Components of the aquaponic system used for the experiments with Nile tilapia and lettuce crops.*

degassing tanks to the hydroponic channels. Two fish rearing tanks fed water into a cone clarifier that in turn fed the water to the first net filter tank. The outflow of the first net filter tank discharged into the adjacent net filter tank from which the water flowed into the degassing tank that in turn distributed the water into three pairs of aquaponic channels by gravity. One channel of each of the three pairs received the water from the degassing tank and fed it to the other adjacent channel of each pair. The outflow of the adjacent channel of each pair joined and emptied into the sump tank by gravity, and water in the sump was pumped back to the fish rearing tanks. The sump contained an automatic switch valve to maintain the water level in the sump and to regulate the pump.

Experimental Conditions

All four fish rearing tanks were stocked at a density of 160 fish/m^3 with mixed-sex Nile tilapia on December 3, 2001. Tank 1 was stocked with 1200 fish each weighing 42.5 g, Tank 2 was stocked with fish each weighing 74.8 g, Tank 3 was stocked with fish each weighing 138 g, while Tank 4 was stocked with fish weighing 248 g each. Different initial weights of the fish at first stocking were chosen to enable staggered harvesting; thus, one tank of the system could be harvested and restocked at a time while the next tank approaches the minimum harvest weight (>250 g/fish) after 6–8 wk of the previous harvest from the system. Floating pellets containing 34% protein were used to feed the fish at different rates (3% body weight/d in tanks that contained fish with an average weight under 100 g and 2% body weight/d in remaining tanks with fish weighing more than 100 g) to account for about 12 kg of feed per day in the system. Biomass in the different tanks was determined by taking subsamples (10% of population) at every 15 d and feeding rates adjusted accordingly. Daily ration was equally divided into a morning (0800 h) and evening (1600 h) feeding. The water temperature was maintained at 28 ± 1 C by installing heaters with thermostats. Water flow rate was adjusted to be approximately 250 L/min throughout the experiment.

Thirty small fish weighing 30 g each were stocked into each clarifier to enhance the sludge settling. The sludge was collected twice daily from the cone clarifiers, and the water lost because of sludge collection, evaporation, and transpiration by plants was compensated by adding new water to the system through a supply line to maintain the water at a predetermined water level. The amount of sludge collected and water added to the system was recorded daily.

Performance of the cone clarifiers and the hydroponic component was evaluated by comparing concentrations of total ammonia nitrogen (TAN), NO_2–N (nitrite–nitrogen), and accumulation rates of NO_3–N (nitrate–nitrogen). At the end of every 6–8 wk, one tank was harvested, starting with Tank 4. All the fish were weighed to obtain the final biomass and total weight gain. The harvested rearing tank was immediately restocked with 1200 fingerlings (11–42 g each). After the initial harvest, Tank 3 was restocked with a manually hand-sexed all-male population on April 18, 2002, to compare the growth variation among the mixed-sex and all-male population over a 6-mo period in the aquaponic system.

Leaf lettuce crops were transplanted in the aquaponic channels for a production period of 4 wk/crop. Initially, only two channels (71 m^2 plant growing area) were transplanted at a density of 42 plants/m^2 with 3-wk-old seedlings grown in peat moss medium in the greenhouse. After the harvest, a similar trial was repeated for three times. Following the first set of four trials in two channels that lasted little more than 4 mo, four channels (142 m^2 plant growing area) and thereafter all six channels (213 m^2 plant growing area) were planted in sets of four trials, each with the lettuce at a same plant density. Therefore, at a fixed density (42 plants/m^2), there were three fish feed to plant growing area ratios: 169, 113, and 56 g/m^2/d. The transplants were placed along with peat moss in plastic net pots (5 cm diameter, 5 cm height), which were inserted into holes made in the floating styrofoam rafts. As many holes were cut in the rafts as to get 42 plants/m^2 of the surface; thus, a total 2982 lettuce plants were transplanted in a pair of channels.

Water Quality and Nutrient Analysis

Water samples were collected twice weekly at 0800 h from the fish culture tanks, cone clarifiers, degassing tank, proximal part of the hydroponic channels, and the sump. Samples were analyzed for TAN, NO_2–N (nitrite–nitrogen), and NO_3–N (nitrate–nitrogen) by using standard methods (APHA 1992). Values of water temperature, pH, dissolved oxygen (DO), TDS, free CO_2 (carbon dioxide), phosphorus, and potassium were determined at weekly interval following standard methods (APHA 1992).

Major nutrients in the lettuce plants were also determined and their values were compared with the chemical constitution of Hoagland's hydroponic solution as well as normally grown plants.

Calculations

Daily weight gain (DWG) expressed as g/fish/d, net yield (NY) expressed as g/m³/d, and feed conversion ratio (FCR) were calculated by using the following formulae:

$$\text{DWG} = (\text{final weight} - \text{initial weight})/\text{no. of fish}/\text{time(d)};$$

$$\text{Net yield (NY)} = (\text{final biomass/m}^3 - \text{initial biomass/m}^3)/\text{time(d)};$$

$$\text{FCR} = \text{total dry feed weight}/(\text{final fish biomass} - \text{initial fish biomass}).$$

Results and Discussion

The system maintained favorable water quality throughout the experiment (Table 1). DO averaged 5.5 mg/L (range 3.99–6.7 mg/L) in the rearing tanks. TAN in the effluent from the hydroponic channels containing plants averaged 1.2, 1.1, and 0.8 mg/L, while nitrite–N (NO_2–N) averaged 0.8, 0.5, and 0.02 mg/L at three

TABLE 1. *Some major chemical parameters in the water of aquaponic fish rearing tanks over a period of 13 mo. Average of 2 samples/wk from all four aquaponic fish rearing tanks.*

Parameters (mg/L)	December 2001	January 2002	February 2002	March 2002	April 2002	May 2002	June 2002	July 2002	August 2002	September 2002	October 2002	November 2002	December 2002	Range	Mean ± SD
CO_2	9.7	9.5	6.7	5.8	7.8	8.6	6.6	7.3	7.6	7.8	7.1	7.5	7.7	5.8–9.7	7.7 ± 1.1
DO	4.0	4.4	4.3	5.2	5.2	5.6	6.3	6.1	5.7	6.1	5.7	6.7	6.5	4.0–6.7	5.5 ± 0.9
pH	7.9	7.7	7.8	7.9	7.9	8.0	8.2	8.1	8.2	8.1	8.0	8.3	8.1	7.7–8.3	8.0 ± 0.2
NO_2–N	0.4	0.5	0.5	0.7	0.8	0.6	0.4	0.6	0.4	0.6	0.6	0.6	0.6	0.4–0.9	0.6 ± 0.2
NO_3–N	20.8	32.4	21.3	22.3	20.3	14.5	5.0	9.7	16.0	22.5	26.7	21.1	22.5	5.0–32.4	19.6 ± 7.0
NH_3–N	2.1	1.7	1.2	1.5	1.2	1.2	1.6	1.1	1.2	1.4	1.1	1.0	1.1	1.0–2.1	1.3 ± 0.3
TDS	1356	1523	1530	1367	1426	1318	1168	1256	1298	1278	1498	1170	1256	1168–1530	1342 ± 123

DO = dissolved oxygen; TDS = total dissolved solid.

different plant growing surface areas (thus, three ratios of fish feed to plants), respectively. These data indicate that the hydroponic component treated the water effectively by removing toxic nitrogen metabolites, and the water quality was relatively better when all six hydroponic channels were transplanted providing 56 g fish feed/m^2 of transplanted surface area. The average temperature was 27.5 C (25.5–29.6 C), and pH averaged 8.1 (7.7–8.3) in the effluent from hydroponic channels.

The final mean weight for the mixed-sex tilapia produced from seven harvests in the aquaponic system was 285.3 g/fish, whereas in the second harvest of Tank 3 where all-male population was stocked, the fish achieved a mean weight of 318.9 g (Table 2). The final average biomass of 43.8 kg/m^3 (average net production 32 kg/m^3) was harvested from the seven harvests of mixed-sex tilapia at an average growth rate of 1.2 g/fish/d. However, final biomass in Tank 3 with all-male population was recorded to be 50.6 kg/m^3 (net production 44.3 kg/m^3) at a growth rate of 1.5 g/fish/d. Thus, an average net production from total eight harvests (mixed-sex as well as all-male tilapia) during the experiment was 33.5 kg/m^3. FCR averaged 1.4 for the mixed-sex population and 1.3 for all-male tilapia. The specific growth rate (SGR) values were 1 and 1.1% for mixed-sex and all-male tilapia, respectively. Survival was lowest for mixed-sex tilapia averaging 95.8% compared to 99% for all-male tilapia.

Lettuce plants with average weights of 157, 212, and 289 g were produced at a density of 42 plants/m^2 in growing areas of 213, 142, and 71 m^2, respectively, in the aquaponic system. For larger growing areas, the inadequate nitrogen, phosphorus, and potassium (NPK) induced lettuce plants to bolt and encourage the development of very tender open-headed lettuce (increased removal of minerals by plants).

Water Quality

A minimum DO concentration of 5 mg/L is required for proper functioning of a recirculating system (Greiner and Timmons 1998). DO values fluctuated from 4 to 6.7 mg/L with an average of 5.5 mg/L in the rearing tanks of the aquaponic

TABLE 2. *Growth data of Nile tilapia during the 13-mo operation of the aquaponic system (mixed sex and all males).*

Parameters	Tank 4	Tank 4	Tank 3	Tank 2	Tank 2	Tank 1	Tank 1	Average	Tank 3
Period	December 03 to February 11, 2002	February 11 to August 24, 2002	December 03 to April 15, 2002	December 03 to May 22, 2002	May 23 to November 21, 2002	December 03 to July 02, 2002	July 03 to December 30, 2002		April 16 to October 24, 2002
Days	70	194	132	140	182	210	179		186
Sex	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	All males
Initial weight (g)	248	11.6	115	65	34.4	42.5	12.1		42
Total initial biomass (kg)	285.1	13.9	138	74.8	41.5	51	15.1		46.8
Initial biomass (kg/m^3)	38	1.6	18.4	10.0	5.5	6.8	2.0		6.2
Final weight (g)	264.1	340.6	291.2	256.3	269.4	290.2	285.6	285.3	318.9
Total final biomass (kg)	317.2	399.9	326.7	287.8	314.9	332.3	319.9	328.4	379.2
Final biomass (kg/m^3)	42.3	53.4	43.6	38.4	42.0	44.3	42.7	43.8	50.6
Growth rate (g/fish/d)	0.2	1.7	1.3	1.4	1.3	1.2	1.5	1.2	1.5
Net yield (g/m^3/d)	61.3	265.3	190.6	202.9	200.3	178.8	227	189.5	238.3
Production (kg/m^3)	4.3	51.5	25.2	28.4	36.5	37.5	40.6	32.0	44.3
Feed conversion ratio	1.4	1.0	1.4	1.7	1.5	1.5	1.2	1.4	1.3
SGR (%/d)	0.1	1.6	0.7	1.0	1.1	0.9	1.8	1.0	1.1
Survival (%)	96.1	97.8	93.5	97.7	97.1	95.4	93.3	95.8	99.0

system. Accumulation of free CO_2 lowers the pH in recirculating aquaculture systems especially when alkalinity is low. Free CO_2 concentration of more than 50 mg/L is reported to be toxic for most fish species (Heinen et al. 1996). The average concentration of free CO_2 in the fish rearing tanks was 7.7 mg/L (ranging from 5.8 to 9.7 mg/L). pH is an important water quality parameter in recirculating systems. As pH decreases, ammonia is converted into a less toxic ammonium form. Therefore, the increase in pH leads toward the accumulation of toxic unionized ammonia in the system (Lawson 1995). The optimum pH range for nitrifying bacteria is between 7.0 and 8.0, and below a pH of 6.8, nitrifying bacteria are inhibited (Michael et al. 1995). The pH was found to occur within its optimum range in the aquaponic system.

TAN in the fish culture effluents averaged 1.2, 1.1, and 0.8 mg/L when two, four, and six channels were transplanted, respectively. Using the mole fraction of unionized ammonia in the water following the method described by Huguenin and Colt (1989) at 28 C temperature and a pH of 8, the corresponding unionized NH_3 levels were calculated to be 0.08, 0.07, and 0.05 mg/L, respectively. According to Popma and Masser (1999), NH_3 values should be less than 0.09 mg/L for optimum tilapia production, although acute toxicity begins at 2.0 mg/L. Thus, the unionized ammonia occurred within the safe limit in aquaponic effluents. In general, NO_2 should not exceed 5 mg/L for tilapia culture (Losordo 1997). The range of NO_2 was between 0.02 and 0.8 mg/L in the aquaponic effluent and was, therefore, within safe limits.

Fish Production

Growth and production of tilapia in the aquaponic system are computed in Table 2. The harvest weight and net weight gain in eight harvests during 13 mo of operation averaged 44.6 kg/m^3 (range 38.4–53.3 kg/m^3) and 33.5 kg/m^3 (range 25.2–51.5 kg/m^3), respectively. Data collected in 13 mo show that the total annual harvest from the four fish culture tanks (total culture water volume 30 m^3) of the aquaponic system was 2677.8 kg, while the net weight gain or production was 2011.6 kg. Survival in 13 mo of operation was 97.5% (range 93.3–99%). An overall FCR averaged 1.4 ranging from 1 to 1.7 in the aquaponic system. Significant differences ($P < 0.05$) were observed in the growth and production values from the single harvest of the trial with all-male tilapia compared to average production from seven harvests with mixed-sex fish. Final weight of the fish from the all-male harvest was calculated to be 318.9 g/fish, whereas it averaged only 285.3 g/fish for mixed-sex population. Similarly, the growth rate, FCR, and SGR of all-male fish were also better (1.5 g/fish/d, 1.3, and 1.1, respectively) than that of the mixed-sex tilapia (1.2 g/fish/d, 1.4, and 1, respectively).

Rakocy et al. (1997) also reported better values of the total harvest weight, net weight gain, mean weight, and growth rate for tilapia in the aquaponic system averaging 81.1 kg/m^3, 73.2 kg/m^3, 487.2 g, and 2.9 g/fish/d, respectively. This is because they reared all-male red tilapia, stocked at higher density (182–227 fish/m^3), and achieved the benefits of a higher density and growth advantage of males over females as males grow faster than females by saving energy for growth that is otherwise spent in egg production in females. Lower FCR and SGR values were obtained because of the limited feeding in order to maintain a constant feeding rate (12 kg feed/d) throughout the operation.

In the present study, mixed-sex Nile tilapia were reared at a density of 160 fish/m^3, except for one instance in a tank when the all-male population was reared for comparing the results. Nile tilapia were selected for rearing in the system because of their adaptability to the local climatic conditions and demand. The fish is well established under Saudi conditions and tolerates wide fluctuations in the water quality parameters.

Water Conservation

Compared to extensive and semiintensive culture practices where 20–25% of the water is exchanged daily to produce 8–15 kg fish/m^3 of water, the aquaponic system produced 45 kg fish/

m^3/crop along with 42 heads/m^2/crop of lettuce with an addition of only 1.4% of total water in the system daily.

There is a large requirement (more than 5 m^3) of water to produce 1 kg of fish in extensive systems, whereas more than 2.5 m^3 of water is needed to produce same weight of fish in semi-intensive aquaculture. In contrast, production of 1 kg of tilapia requires only 0.32 m^3 water in the aquaponics. Rakocy et al. (1997) have reported even less water usage (0.25 m^3 for each kilogram of fish production) in aquaponics because they stocked higher density of all-male red tilapia. An aquaponic system has the added advantage that it also produces vegetables as a by-product in the hydroponic component. Very little water is used in vegetable production under aquaponics compared to their production in land agriculture. As opposed to land agriculture, where the major portion of irrigation water percolates into the soil while the plants use relatively little water, the aquaponic effluents remain in continuous circulation within the system so that the only losses are as a result of evaporation and transpiration.

Nutrients in Aquaponics

Lettuce in the hydroponic component provided adequate waste treatment. The available phosphorus (P) and potassium (K) in the aquaponic system were well below the standard requirements in hydroponics (Table 3). Phosphorus averaged 10.3, 4.9, and 3.6 mg/L, while potassium values were 47.5, 31.4, and 19 mg/L in the trial with fish feed to plant growing area ratios of 169, 113, and 56 g/m^2/d, respectively. These results show that NPK always occurred at low concentrations in the water and never exceeded the threshold concentration; hence, they should never accumulate in excess concentrations either in the water or in the plant tissues. Moreover, the concentrations of NPK in the water of the hydroponic channels decreased as the cultivated area (plant population) increased because of increased uptake of these minerals by lettuce plants. Maximum plant growth in integrated systems requires proper nutrition, for instance the Hoagland's nutrient solution, consisting of six macronutrients (ppm): N (210), P (31), K (234), Ca (160), Mg (45), and S (64) and six micronutrients (ppm): Fe (0.6), Mn (0.5), B (0.5), Zn (0.05), Cu (0.02), and Mo (0.02).

The prevalence of nutritional deficiencies and yield reduction in plants under recirculating systems in prior studies, caused by deficient nutrient solutions and excessive salt accumulation, indicated that optimal hydroponic concentrations cannot be maintained over prolonged periods of time if commercially available diets are used (Van Toever and MacKay 1981; Sutton and Lewis 1982; Burgoon and Baum 1984; Nair et al. 1985; Zweig 1986; Rakocy and Nair 1987; Rakocy 1989; Rakocy et al. 1989; Clarkson and Lane 1991; Rakocy et al. 1993). As a result, nutrient concentrations must be continuously monitored, and nutrient supplementation and water replacement must be used to correct for nutrient deficiencies and salt accumulation, respectively.

In this experimental aquaponic system, fish were fed a 34% protein feed at ratios of 56, 84, and 168 g fish feed/m^2/d for three hydroponic surface area (213, 142, and 71 m^2) to optimize the integrated system (preventing nutrient accumulation or deficiency) to produce vegetables at their potential capacity and allow proper nutrient removal by plants to improve the quality of the effluent to enhance fish production. The pH in the system averaged above 8, and according to Resh (1991), a pH of 7.5, while

TABLE 3. *Values (mg/L) of nitrogen (N), phosphorus (P), and potassium (K) in Hoagland's nutrient solution (*H*), aquaponic water (*W*), aquaponic lettuce plant (*L_A*), and standard lettuce plant (*L_S*).*

	N				P				K			
Cultivated area (m^2)	*H*	*W*	L_A	L_S	*H*	*W*	L_A	L_S	*H*	*W*	L_A	L_S
71	210	6.1	614.1	2800	31	10.3	13.7	190	234	47.5	78.1	1500
142	210	5.6	341.5	2800	31	4.9	15.1	190	234	31.4	74.2	1500
213	210	2.3	172.7	2800	31	3.6	13.3	190	234	19.0	64.1	1500

near optimal for nitrification, is suboptimal for the availability of P, Fe, Mn, B, Cu, and Zn to the plants. However, there were no observed nutrient deficiency symptoms that appeared on lettuce during the 13-mo trial, although the levels of most nutrients were always below the initial concentration of nutrients in hydroponic formulations (e.g., Hoagland's). Nutrient solutions in hydroponics are supplied by dissolving salts in water to make a nutrient solution that lasts over a period of time and depletes in strength until it is replenished or changed. Contrasting to this, in aquaponics, nutrients are constantly created from the waste metabolites. Staggering plant production in aquaponics helps maintain a constant nutrient uptake, thereby maintaining a nutrient balance and ensuring that nutrients never accumulate to toxic levels.

According to Rakocy et al. (2004), aquaculture effluent provides most of the nutrients required by plants if the optimum ratio between daily feed input and plant growing area is maintained. Manipulating the mineral contents of diets used in integrated systems has been suggested as a means of influencing the rates of accumulation of nutrients and reducing or obviating the need to supplement nutrients artificially (Seawright 1993). Feed to hydroponic surface ratio of 56 g/m^2 in this study was observed to be excellent in limiting nutrient buildup as also reported to be optimal for lettuce production by Rakocy et al. (1997).

Lettuce Production

In the first set of four trials when only two channels with a surface area of 71 m^2 were used to grow plants, a total of 11,822 leaf lettuce seedlings were transplanted, and at the end of the growth period, 10,632 plants were harvested with an average weight of 289 g. During the second trial, conducted in four channels with a surface area of 142 m^2, 16,108 plants with an average weight of 212 g were harvested out of the total 17,305 initial transplants. In the third set of four trials, about 25,891 lettuce seedlings were transplanted within a surface area of 213 m^2, and 23,867 lettuce heads were harvested weighing 157 g each. Thus, a total of 50,607 lettuce plants were produced within one complete year in the aquaponic system. Rakocy et al. (1997) have reported an annual production of 1248 cases (24–30 heads/case) of lettuce making a total of 34,000 lettuce heads with the weight ranging from 181 to 344 g for romaine lettuce. The lower annual lettuce production in a similar study by Rakocy et al. (1997) was because of a lower density of 16–20 plants/m^2 used to grow lettuce crop in an outdoor aquaponic system.

According to Rakocy (1999), the yields from aquaponic systems are greater than those for plants grown in soil under similar conditions. The aquaponic system at the University of Virgin Islands produced 13 crops/yr compared to 4–5 field crops/yr. Moreover, the plant density (16 plants/m^2) is four times greater than the density (4 plants/m^2) typically used in field production. In the present aquaponic trial, even a higher density (42 plants/m^2) was used, which is equivalent to 10 times that from the field production of lettuce.

Component ratios in aquaponics is an important factor, and Rakocy (1989) and Rakocy et al. (1993) examined the effect of varying the ratios of plants to fish (numbers), ranging from 1.2 to 7.5, on the production of lettuce and the total accumulation of salts using standard fish diets. They determined that maximum plant yield occurred at a ratio of 1.9 plants (romaine lettuce, *Lactuca sativa*) to fish (Nile tilapia). Comparative yield of lettuce at three ratios (0.6, 1.2, and 1.9) of plants to fish (numbers) in the present study also confirms the findings of Rakocy (1989) and Rakocy et al. (1993). However, bolting and open-headed lettuce production in the present study may have been caused by the high plant density. This may need to be decreased to 25–30 plants/m^2 to produce a better quality lettuce.

Conclusion

The aquaponic system was simple to manage and recycled more than 98% of its water. It produced more than 40 kg fish/m^3 every 6 mo compared to the semiintensive aquaculture in Saudi Arabia where 20–30% of the water is exchanged daily to produce 8–15 kg fish/m^3 of water. The system used 320 L of water for 1 kg of fish produced compared to more than 2000 L for producing the same biomass in semiintensive systems. Aquaponics further economizes the conservation of water and operational cost by producing 42 lettuce heads/m^2 every month at little additional cost. It was determined that a fish feed to hydroponic surface ratio of 56 g/m^2 was excellent to control nutrient buildup; however, plant density could be decreased from 42 to 25–30 plants/m^2 to get marketable lettuce.

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