Food Value, Water Use Efficiency, and Economic Productivity of an Integrated Aquaculture-Olericulture System as Influenced by Tank to Biofilter Ratio

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Summary. Fish and vegetable production were linked in a recirculating water system. Hybrid tilapia (*Oreochromis mossambicus* (Peters) x *O. niloticus* L.) were grown in tanks and fed a commercial feed. Tomato (*Lycopersicon esculentum* Mill. cv. Laura) was grown in the summer of 1988, cucumber (*Cucumis sativus* L. cv. Fidello) in the fall of 1988, and 'Kewalo' tomato in the spring of 1989 in a Raleigh, N.C. greenhouse. Four tank to biofilter volume ratios were studied to determine composite food production and resource utilization efficiency from this system. Plants were grown in biofilters at 4 plants/m^2 and surface irrigated 8 times daily with water from an associated fish tank. Biofilter drainage returned to the fish tanks by gravity. Each system received identical nutrient inputs and plants received equal water. Water quality was maintained within limits suitable for tilapia production by biological filtration, aeration, and mineral assimilation by plants. Dissolved oxygen levels, total water consumed, fish biomass and growth rates increased with biofilter volume. Total fruit yield increased but yield per plant decreased with increasing biofilter volume. Fish yield, expressed as calories or protein of the edible portion of the increase in biomass, produced per liter of water consumed tended to decrease with increasing biofilter volume. Calories and protein of tomato per liter consumed did not exhibit a consistent trend. Total calorie production of the edible portion of fish and fruit per liter of water consumed decreased with increasing biofilter volume. Total protein production of the edible portion of fish and tomatoes per liter of water consumed decreased with increasing biofilter volume. Total calorie and protein production increased with biofilter volume irrespective of water use.

In arid and semiarid regions, agriculture creates a heavy demand on water resources, and returns in terms of productivity are low (Kowal and Kassam, 1978). "Production of fish from natural waters or by aquaculture is both feasible and highly desirable in arid zones." (Welcomme, 1977). Integrating aquaculture with olericulture includes the following benefits: conservation of water resources and nutrients, high levels of fish and vegetable production per unit of area, and increased food value and protein production per unit of water volume (Rakocy, 1989a; McMurtry et al., 1990). The constraints of water supply, soil type, and land availability typically limit the utilization of pond or cage aquaculture systems but do not limit the use of recirculating systems (Rakocy, 1989b). Integrated systems use less than 1% of the water required in pond culture for equivalent tilapia yields (Rakocy, 1989a; McMurtry et al., 1990). Such symbiotic systems are applicable to the needs of arid or semi-arid regions where fish and fresh vegetables are in high demand (Rakocy, 1989a). “The expansion of aquaculture should be given high priority in developing and developed countries.” (World Comm. on Environment and Development, 1987).

Recirculating aquacultural water has potential for hydroponic cultivation of higher plants (Naegal, 1977; Lewis et al., 1978; Watten and Busch, 1984; McMurtry et al., 1990, 1993a, 1993b). Aquacultural water has been successfully employed to grow many different vegetable species in biofilters operated on a reciprocative flow basis (McMurtry et al., 1990,1993a, 1993b). Previous integrated fish-vegetable systems have removed suspended solids from the water by sedimentation in clarifiers prior to plant application (Rakocy, 1989a). Removal of these solids resulted in insufficient residual nutrients for good plant growth. Acceptable fruit yields in integrated systems have only been achieved with substantial supplementation of plant nutrients (Lewis et al., 1978, 1981; Rakocy 1989a).

Reciprocating biofilters, which are alternately flooded and drained, provide the advantages of uniform distribution of nutrient-laden water in the filtration medium during the flood cycle and improved aeration from atmospheric exchange with each dewatering (Lewis et al., 1978; McMurtry et al., 1990; Paller and Lewis, 1982; Rakocy, 1989b). These advantages benefit both nitrifying bacteria and plant roots (Lewis et al., 1978; Paller and Lewis, 1982; Rakocy, 1989a). Aqueous nitrate concentrations in recirculatory aquaculture have been adequately regulated when integrated with vegetable crops on a reciprocative flow basis (Lewis et al., 1978; Watten and Busch, 1984; Rakocy, 1989a; McMurtry et al., 1990).

One objective of this study was to evaluate both fish and vegetable yields and composite production per unit of water volume consumed as influenced by tank to biofilter (v/v) ratio. Increased efficiency of water utilization in food production (e.g., grams of protein/liter and Kcal/liter) was a fundamental impetus in the development of this technique. Another objective was to project economic productivity per unit of composite production area as influenced by tank to biofilter ratio.

Materials and Methods

Olericulture was integrated with recirculatory aquaculture in a greenhouse in Raleigh, N.C. (McMurtry, 1990; McMurtry et al., 1993a, 1993b). All-male (sex-reversed) hybrid tilapia (*Oreochromis mossambicus* (Peters) x *O. niloticus* (L.), *Cichlidaceae*) were cultivated in 500 liter in-ground tanks with aeration provided by regenerative blowers at 0.7 liter/s through two air stones (3.8 x 3.8 x 15 cm) per tank. Water temperatures were kept above 25°C by two 250W thermostatic aquaria heaters (Visitherm, Mentor, OH) per tank. The rectangular tanks were formed with plywood, the bottoms sloped to 45 degrees, and were lined with 0.50 mm (2 @10 mil) black

Figure 1 polyethylene (Figure 1). Each tank was coupled to a biofilter employing a builder's grade sand as substrate. Tank water level at capacity was 10 cm below the bottom of the biofilter.

Four tank to biofilter volume (BFV) ratios, bracketing that used in preliminary studies (McMurtry et al., 1990), were selected as treatments. Biofilters were 1.2 m wide, 0.33 m deep and of variable length to achieve 4 ratios by volume (v/v) to the fish tank

Table 1 (Table 1). Biofilters were lined with 0.45 mm (three @ 6 mil) polyethylene plastic and the bottom sloped 1 : 200 along the length to direct drainage for return to the associated tank. The biofilter media composition was 99.25% quartz sand and 0.75% clay.

Each experiment was conducted as a randomized complete block design with four replicates. Multiple daily observations of water quality measurements were averaged. Analyses for factorial experiments were made with Statview 512+ (Abacus Concepts, Berkeley, CA) on a PC. One-factor multi-comparison ANOVA tests were conducted for a significance level of $P \leq 0.05$. When results of F tests warranted, LSDs were calculated.

Irrigation water was drawn from the bottom of the fish tanks at evenly spaced intervals 8 times daily between dawn and sunset and pumped to the biofilter surface at 500 liters/m^2/d (Table 1). Tanks were filled with city water equal to evapotranspiration losses when tank volumes fell below 75% of capacity. The number of tank water exchanges was calculated as the percentage of total tank volume exchange daily multiplied by the duration of the fish culture interval. The total number of irrigations applied to vegetable crops was calculated as the number of irrigation events per day multiplied by the duration of the vegetable cropping interval. Water pH in the tanks was monitored daily and amendments of lime ($CaMg [CO_3]_2$) or calcium oxide (CaO) were made to raise pH levels above pH 6.0 if and when the water fell below pH 5.5 in a majority of replicates of each

Table 2 treatment (Table 2).

Total water consumption was calculated as the sum of the replacement volumes inputs made during each experiment as required to reestablish each system to full capacity. Since the volume, which remained in the system at termination of each experiment, equaled full capacity (initial volume) it was not included as water consumed or included in the calculations of crop applications per liter consumed. The number of crop applications per liter was calculated as the total number of times each liter of water was employed to irrigate the vegetable crop plus the number of times it was returned to the tank for fish production. Therefore, the total number of crop applications per liter was calculated as twice the water volume moved divided by the total volume consumed.

The fish were fed a diet of modified Purina Fish Chow 5140, with a minimum analysis of 32% crude protein, 3.5% crude fat, and not more than 7.0% crude fiber. The feed was not fortified with vitamins or trace elements. Feed composition is reported in

Table 3 Table 3 . The daily feed input rate was established as a variable percentage of standing fish biomass as influenced by age and mean individual weight (Pullen and Lowe-McConnell, 1982). Feed rate was adjusted uniformly based upon the previous monthly mean feed conversion ratio (data not shown). The daily ration was divided equally into two feedings administered at 0800 and 1300 hours. The fish also grazed algae (*Oscillatoria Vaucher* spp., *Cyanophyta* and *Ulothrix Kützing* spp., *Chlorophyta*) that grew in the water and on the tank sides.

The number of fish stocked, the mean individual and total initial biomass, the daily feed input rate, the feed conversion ratio, the mean individual and total ending biomass, and

Table 4 monthly production (growth) rate during each crop interval are reported in Table 4. Fish biomass was determined monthly by first removing all fish from each tank. Each fish was individually sedated with Quinaldine, blotted dry, and weighed. The individual weights of the fish in each tank were summed. Fish biomass increase per time interval was calculated by subtraction of the stocked biomass from the ending biomass. Total fish biomass per tank was adjusted to uniform levels across treatments monthly. Individual fish were returned to the identical tank with stocked total biomass adjustments made (a minimum number of individual fish added or removed) such as to maintain a uniform (±2.5%) biomass and a uniform number of individuals between all tanks.

The edible portion of fish biomass produced (gained) was calculated as 50% of the increase in live weight. The fish protein and lipid fractions were calculated at 17.6% and 8.1% of the edible portion (Viola and Amidan, 1980). Caloric content of the edible fish biomass was calculated at 4 kcal/g for the protein fraction and 9 kcal/g for the lipid fraction

Vegetable seedlings were transplanted into each biofilter at 4 plants/m^2 resulting in 4, 6, 9, or 14 plants per biofilter (Table 1). Tomato fruit were harvested at the incipient color stage and weighed by grade from each plot. Fruit were graded as No. 1 if blemish free and greater than 100 g, as No. 2 if greater than 50 g but having minor blemishes, and otherwise were culls. Cucumber fruit were harvested when they attained 5 cm in diameter.

The edible portion of tomato fruit was calculated as 100% of the Grade No 1 and Grade No. 2 yields. The protein content of the tomato and cucumber fruit was calculated at 1.1 and 0.9 g/100 g (%) of fresh weight, respectively (Lorenz and Maynard, 1980). Caloric content of the tomato and cucumber fruit was calculated at 22 and 15 cal/100 g of fresh weight, respectively (Lorenz and Maynard, 1980).

Insect pests were controlled principally through the use of beneficial insects including *Encarsia formosa* (Gahan) and Lacewings (*Chrysopa carnea* (Stephens)) for greenhouse whitefly (*Trialeurodes vaporariorum* (Westwood)), and Ladybugs (*Hippodamia convergens* (Gurin-Mneville)) for potato aphid (*Macrosiphum euphorbiae* (Thomas)). Insecticidal Soap (Safer Inc., Netwon, MA) was applied as necessary to maintain Sweetpotato whitefly (*Bemisia tabaci* (Gennadius)) populations below threshold levels.

In order to estimate yearly income from two market sizes of tilapia, projected yearly fish growth rates in each treatment were estimated from linear regressions of the mean individual increases in fish weight from 14 g to 214 g and from 14 g to 442 g (McMurtry, 1990). Economic yields for fillets were calculated for the 214 g fish at 40% of live weight with a market value of $3.00/kg and for the 442 g fish at 50% of live weight with a market value of $4.40/kg. Projected yearly yield of 'Laura' tomato in each treatment was estimated for trusses 1-8 at twice the mean yield of trusses 1-4 with 3 crops grown per year. Projected yearly yield for 'Kewalo' tomato in each treatment was estimated at 3 times the yield of trusses 1-8 for 3 crops per year. Fruit quality grade distribution was assumed to be 60% Grade No. 1, 30% Grade No. 2 and 10% defective. Market values of grades 1 and 2 were calculated at $2.20 and $1.32 per kg, respectively. Disposal costs of defective fruit was estimated at $0.05 per kg. Production value per composite unit area was calculated from the addition of the gross values returned from 442 g fish and the respective crops divided by the combined fish tank and biofilter area of each treatment ratio.

Experiment 1. Fish were stocked on 5 May 1988 at uniform stocking density, mean individual weight, and total biomass (Table 4a). Tomato (*Lycopersicon esculentum* Mill. cv. Laura) was transplanted 13 May 1988 and grown as a single-stem for 103 days. Fruit set only on trusses 1-4 because of excessive heat (≥40C) after 22 June (McMurtry et al., 1993a).

Experiment 2. Fish were stocked on 25 August 1988 at uniform density, mean individual weight, and total biomass (data not shown). The system was irrigated and fish feeding continued for 42 days without plants grown in the biofilters to assess whether or not plants were contributing to pH buffering of the water (McMurtry, 1990). Water pH fell rapidly to below pH 4.0 and incremental amendments with lime ($CaMg[CO_3]_2$) were made totaling 2.0 kg per biofilter in an effort to raise water pH and reestablish nitrification prior to replanting (Table 2). The fish were harvested 42 days after stocking (data not shown).

Fish were restocked on 06 October 1988 at uniform density, mean individual weight, and total biomass (Table 4b). A parthenocarpic greenhouse cucumber (*Cucumis sativus* L. cv. Fidello) was transplanted 07 October 1988 and grown as a single-stem for 85 days. Water pH was too low (data not shown) for proper nutrient assimilation by cucumber and calcium oxide (CaO) was added approximately twice weekly in quantities sufficient to raise water pH above 6.5 following each application (McMurtry, 1990). Total lime and CaO inputs are shown in Table 2.

Experiment 3. Fish were stocked 5 Jan 1989 at uniform density, mean individual weight, and total biomass (Table 4c). The semi-determinate, bacterial wilt-resistant tomato variety ‘Kewalo’ was planted 5 January, 1989 and grown as a single-stem for 132 days (McMurtry et al., 1993a, 1993b).

Results

Experiment 1, 2 and 3. Total water volume consumed increased with increasing BFV (Table 5). The number of tank volume exchanges (tank volumes recycled) increased with increasing BFV due to the scheduling of irrigation proportional to BFV (equal water volume and frequency per plant). The volume of replacement water to compensate for evapotranspiration increased with increasing BFV and ranged from 1.2% to 4.7% of the system capacity per day (data not shown). The number of crop irrigations to the plant crop was identical in all treatments. The number of water applications per liter consumed increased with increasing BFV (Table 5).

Table 5

Experiment 1. Fish biomass increase per liter of water consumed decreased or tended to decrease with increasing BFV, while fruit yield per liter did not differ significantly between treatments which was attributed to water pH(Table 5a). Total calories and protein per liter of water consumed both decreased with increasing BFV for tilapia and increased with increasing BFV for tomato (Table 6a). Total caloric value and total protein produced in the edible portion of tilapia and tomatoes per liter of water consumed decreased with increasing BFV. Total calorie and protein production increased significantly with BFV irrespective of water consumption.

Table 6

Experiment 2. Fish biomass increase per liter of water consumed tended to decrease with increasing BFV but did not differ significantly which was attributed to mean water pH during this crop interval (Table 5b). Cucumber fruit yields per liter of water consumed were not significantly different between biofilter treatments, which was also attributed to water pH. The low pH of the water was the result of the 42 day interval with ‘no crop’ grown the biofilters immediately prior to Experiment 2 (McMurtry, 1990).

Calories from the increase in fish biomass per liter of water consumed tended to decrease with increasing BFV but did not vary with BFV for cucumber fruit (Table 6b). The total energy (calories) represented in the combined outputs of tilapia and cucumbers per liter of water consumed did not vary with BFV, which was attributed to disparate water pH between treatments during this experiment. The calculated protein content of the edible portion of tilapia biomass increase per liter of water consumed did not differ significantly. Total protein represented in the combined tilapia and cucumber fruit outputs per liter of water consumed tended to increase with BFV. Total caloric value and total protein represented in the combined outputs both tended to increase with increasing BFV irrespective of water use.

Experiment 3. Tilapia biomass increase per liter of water consumed decreased with increasing BFV while fruit yield per liter tended to decrease but did not differ significantly between treatments (Table 5c).

Calories from the increase in tilapia biomass decreased with increasing BFV while caloric content of tomato fruit tended to decrease but did not differ significantly between treatments (Table 6c). Total calories per liter of water consumed decreased with increasing BFV. Protein production from the edible portion of the increase in tilapia biomass per liter of water consumed decreased with increasing BFV while protein production per liter of water consumed for tomato fruit tended to decrease but did not differ significantly between treatments. Total protein production from tilapia and tomatoes per liter of water consumed decreased with increasing BFV. Irrespective of water use, total caloric value increased with BFV while total protein represented in the combined outputs tended to increase with BFV but did not differ significantly between treatments.

Projected annual tilapia yield for 214 g and 442 g market-size tilapia increased
Table 7 with increasing BFV (Table 7). Corresponding market values per unit tank volume were estimated to range from \$63 to \$77/m^3/yr for 214 g tilapia (data not shown) and \$91 to \$112/m^3/yr for 442 g tilapia (data not shown). Projected yearly yields for 'Laura' and 'Kewalo' tomato decreased with increasing BFV. The projected yearly market value for the combined production of tilapia and 'Laura' tomato per composite unit area ranged from \$139 to \$104/m^2/yr (Table 7). Substitution of 'Kewalo' tomato for 'Laura' resulted in production values ranging from \$113 to \$64/m^2/yr (Table 7).

Discussion

Yield per plant tended to increase with decreasing BFV (McMurtry et al., 1993a), indicating greater per plant nutrient availability in smaller biofilters (McMurtry et al., 1993b). Plant uptake of anions and cations helped buffer water pH (McMurtry et al., 1993b), which is also indicated by the rapid drop in pH of the water when vegetable crops were not grown in the biofilters. Plant growth in these studies was adequately sustained on minimal nutrient concentrations due to the constant replenishment characteristic of recirculated aquacultural water (McMurtry et al., 1993a, 1993b), and supports the results of other researchers (Lewis et al., 1978; Winsor et al., 1985).

Fish growth rates tended to increase with increasing BFV, which was positively correlated with decreasing feed conversion ratio (FCR), improved water quality, and increased pH buffering with increasing BFV (McMurtry, 1990).

Because the fish in these experiments had been repeatedly sedated with a fat-soluble, potential carcinogen (Quinaldine) in order to aid biomass measurement, the vast majority of these fish were not eaten. Therefore, the question of possible 'off-flavor' in the fish - as caused by a potential for the absorption of water soluble root exudates - was not systematically determined. Additionally, identification of 'off-flavor' is highly subjective and not readily quantifiable. However, randomly selected individual fish, both of those removed at monthly intervals for biomass adjustment and of the final harvest, were 'tested' for flavor. More than ten (10) people each tasted (sampled) from 2 to 10 different fish and no 'off-flavor' fish were detected. Additionally, several hundred fish, which had been grown during two (2) previous studies, which included from 6 to 8 different vegetable species in each biofilter, had been eaten and none were found to be 'off-flavor'. Commercial fish growers typically 'purge' captive-reared fish in 'clean' water for approximately one (1) week prior to marketing in order to minimize any potential for an 'off-flavor' fish reaching the consumer.

The decrease in protein production per unit of water consumed with increasing BFV was attributed to increased evapotranspiration and leakage losses in the larger biofilters, which more than offset the increased rate in fish growth that resulted from improved water quality conditions from (with) the larger biofilters. Improved water quality with increasing filter size was attributed to the greater available surface area for microbial attachment sites and to a greater root mass (more plants and greater rooting volume) which increased the percentage of fish metabolites assimilated by the plants (McMurtry et al., 1993b). The total (composite) caloric value of outputs per liter of water consumed decreased with increasing BFV, however total calories produced increased with BFV which was attributed to an increased percentage of fish residues assimilated by increasing plant number and increased photosynthetic area with increasing BFV.

As in any system, only one dependent variable can be optimized. If optimal use of nutrient inputs is sought, a high plant number per unit of fish biomass appears to be preferable. However, fruit yield per plant was greatest at low plant populations per unit of fish biomass produced (McMurtry et al. 1993a). If maximal fish production per composite unit area (combined tank, biofilter, and aisle areas) is sought, a low plant population per unit of fish biomass production is preferable because a higher percentage of the composite area would be apportioned to fish production.

The pH of the water remained below 7.0 indicating that the largest percentage of the ammonia resultant from fish metabolism remained in ionized form (relatively non-toxic to fish). Subsequent microbial conversions and plant assimilation of nitrogenous compounds maintained water quality suitable for tilapia production (McMurtry, 1990; McMurtry et al., 1993b). When N assimilation rates approximated the N input rate, alkaline amendment was not necessary in this system (McMurtry, 1990).

Uniform crop development and satisfactory performance of this system can be attributed in part to the reciprocating water movement. This movement ensured an even distribution of nutrients and O_2 to all plant roots by drawing atmospheric O_2 through the medium during every drainage period (McMurtry et al., 1990; McMurtry, 1990).

This co-culture technique appears to have greater potential for profit than traditional commercial greenhouse tomato production which is valued at \$62/m^2/yr (with 2 crops/yr) under identical fruit quality distribution and market value assumptions (Brumfield et al., 1981). The combination of aquaculture and olericulture provides an opportunity to increase profitability by increasing per unit area yield rates and by reducing direct costs of production relative to current commercial methodologies constructed and operated separately.

The culture system employed in these studies is simple to operate. Fish stocking density and feed rates are adjusted to optimize water quality parameters for the fish as influenced by plant growth (fish-waste assimilation) rate. Plants are grown using traditional methods excluding any which would be harmful to either the fish or biofilter microbes. Water quality, particularly pH, must be monitored regularly to provide a basis for management decisions such as feed input rate. Plants should be grown in the biofilters on a continuous basis. This may be accomplished through rotational multi-cropping. This polytrophic culture system has substantial potential in areas of limited water supply and/or high land value.

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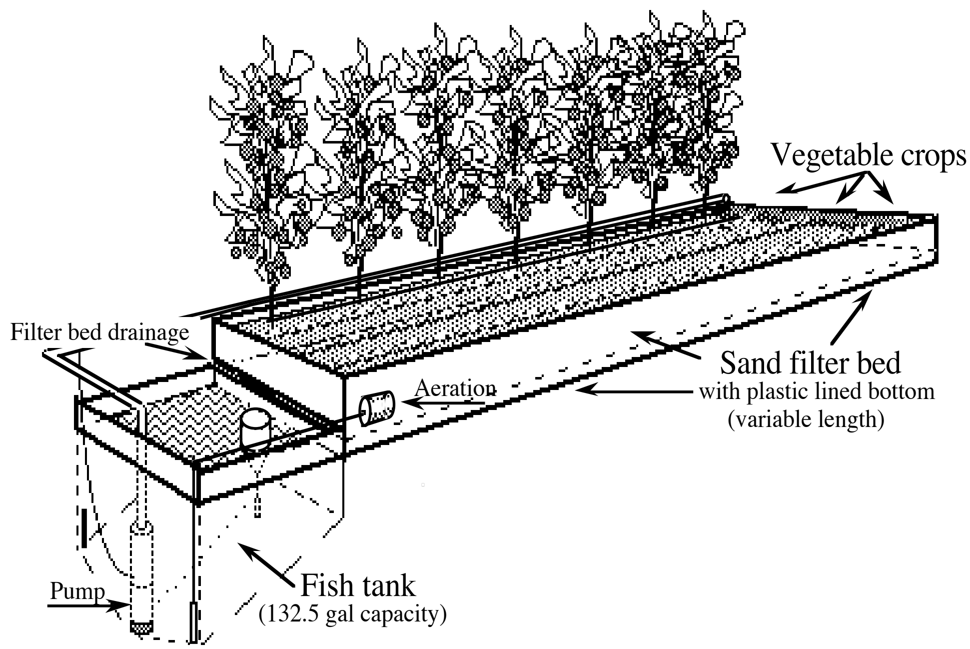

Fig. 1. Schematic diagram of the integrated aquaculture-olericulture system.