Water Quality Maintenance and Mineral Assimilation by Plants Influence Growth of Hybrid Tilapia in Culture with Vegetable Crops[1]

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Additional index words. biofiltration, *Cucumis sativus* , hydroponics, integrated aquaculture, *Lycopersicon esculentum*, olericulture, *Oreochromis mossambicus*, *Oreochromis niloticus*, sand culture.

Abstract. Fish and vegetable production were linked in a recirculating water system. Hybrid tilapia (*Oreochromis mossambicus* (Peters) x *O. niloticus* (L.)) was grown in

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1 Partial funding for this research is from the United States Department of Agriculture Special Grant P.L. 89-106: "Agricultural Adjustment in Southeast Through Alternative Cropping Systems." Additional funding was from a grant by the "Orange Presbytery" of the Presbyterian Church of North Carolina.

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5 The authors gratefully acknowledge the assistance of L. Barrons, M. Buchanan, P. David, DeRuiter Seeds Inc., B. Haning, R. Jones, P. Lineberger, N. Mingis, P. Nelson, R. Patterson, M. Pridgen, C. Prince, C. Spivey, J. Stoop, R. Tucker, Rex Plastics and the University of Hawaii for their help on the project.

tanks and fed a 32% protein feed. Tomato (*Lycopersicon esculentum* Mill. 'Laura') was grown in summer 1988, cucumber (*Cucumis sativus* L. 'Fidello') in fall 1988, and tomato'Kewalo' in spring 1989 in a Raleigh, N.C., greenhouse. Four tank to biofilter volume ratios were studied. Plants were grown in biofilters at 4 plants m^{-2} and irrigated 8 times daily with water from the associated fish tank. Biofilter drainage was returned to the associated tank. Each system received identical nutrient inputs and each plant received equal water. Biological filtration, aeration, and plant assimilation of minerals and N-compounds maintained water quality suitable for tilapia production. Dissolved oxygen levels, make-up water inputs, fish biomass and fish growth rates increased with biofilter volume. Total ammoniacal-N, NO_2^-, and NO_3^- concentrations decreased with increasing biofilter volume. Water pH declined rapidly when the systems were operated without plants. When horticulture was included, water pH remained stable at approximately pH 6.0. Fruit yields per unit increase in fish biomass and per biofilter increased with increasing biofilter volume. Fruit yields and fish biomass increase per plant declined with increasing biofilter volume. Fish growth associated with the largest biofilter was 120% of that associated with the smallest biofilter.

Submitted for publication to The Journal of the World Aquaculture Society, 1994, Paper No. _____ of the Journal Series of the North Carolina Agricultural Research Service, Raleigh, NC 27695-7643. Mention of a trademark, proprietary product, or vendor does not imply its approval to the exclusion of other products or vendors that may also be suitable. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

Introduction

Recirculating aquaculture water has been used for hydroponic cultivation of higher plants (Lewis et al. 1978a, 1978b, 1981; McMurtry 1990; McMurtry et al. 1990, 1993a, 1993b, 1994; Näegal. 1977; Nair et al. 1985; Rakocy 1989a, 1989b; Watten and Busch 1984). All previous plant-integrated aquaculture systems, other than those reported by this author and Rakocy, have specified the removal by sedimentation of more than 95% of the suspended-solid fraction of the waste products from the culture water prior to plant applications (Rakocy 1989b). Hydroponic vegetable production has been demonstrated to reduce NO_3^- concentrations in recirculating aquaculture water (Lewis et al. 1978a, 1978b, 1981; McMurtry et al. 1990, 1993a, 1993b, 1994; Nair et al. 1985; Kane 1987; Rakocy 1989a. 1989b), and eliminated the need for subsequent microbial denitrification.

Biofilters that are alternately flooded and drained were first proposed by Lewis et al. (1978) and are referred to as reciprocating biofilters (RBF). Advantages of a RBF are 1) uniform distribution of nutrient-laden water within the filtration medium during the flood cycle and 2) improved aeration of the biofilter from atmosphere exchange with each dewatering (Lewis et al. 1978; McMurtry et al. 1990; Paller and Lewis 1982; Nair et al. 1985; Rakocy 1989 a). These advantages benefit both the nitrifying bacteria and plant roots (Hopkins et al., 1950; Lewis et al. 1978; Paller and Lewis 1982; Rakocy 1989a, 1989b). Nitrification is limited by oxygen concentrations lower than 2 mg L^{-1}.(Nair et al. 1985) and complete oxidation of 1 mg of NH_3-N requires 4.6 mg of oxygen (Kaiser and Wheaton 1982).

Benefits of integrating aquaculture and vegetable horticulture (olericulture) are: 1) conservation of water resources and plant nutrients (McMurtry et al. 1990, 1993a), 2) intensive production of fish protein and 3) reduced operating costs relative to either system in isolation (McMurtry et al. 1994). The constraints of water supply, soil type

and land availability do not limit the use of recirculating systems as occurs in pond or cage aquaculture (Rakocy 1989a). Water consumption in integrated systems including tilapia production is less than 1% of that required in pond culture to produce equivalent yields (McMurtry 1990; McMurtry et al. 1990, 1994; Rakocy 1989 b).

Such a symbiotic system is applicable to the needs and requirements of arid or semi-arid regions where fish and fresh vegetables are in high demand (Nair et al. 1985; Rakocy 1989b; McMurtry et al. 1990). Organic vine-ripened, pesticide-free produce and 'fresh-daily' fish can bring premium prices, particularly during winter months in urban areas. Markets for fresh fish abound in landlocked regions and overfished coastal areas throughout the world (Nair et al. 1985; Rakocy 1989b).

Proper management of integrated systems requires the maintenance of a nutrient balance to maximize both fish and plant yields (McMurtry et al. 1993a, 1993b; Rakocy 1989 b). The objective of these studies was to evaluate the influence of fish tank to biofilter volume (BFV) ratio on fish growth rate and water quality. Plant assimilation of nutrient residual from fish production (biofilter plant population proportional to BFV) on water quality was evaluated.

Materials and Methods

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 at a flow rate of 0.7 $L \cdot s^{-1}$ through two (3.8 x 3.8 x 15 cm.) airstones per tank. Water temperatures were kept above 25°C by two Visitherm™ 250W thermostatic aquaria heaters per tank. The rectangular tanks were formed with plywood, the bottom sloped to 45° and lined with 0.50 mm (2 @ 10 mil.) black polyethylene (Fig. 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. Biofilters were 1.2 m wide, 0.33 m deep and of variable length to achieve 4 ratios by volume to the fish tank (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. Media composition was 99.25% quartz sand, 0.75% clay, 0.0% silt. The sand fractionation was: very fine sand, 1.1%; fine sand, 5.2%; medium sand, 21.0%; coarse sand, 38.8%; and very coarse sand, 33.3%. Four tank to BFV ratios, bracketing that used in preliminary studies, were selected as treatments (McMurtry et al. 1990). Each tank-to-biofilter ratio was replicated with four independent systems per ratio.

Experiments were conducted in a polyethylene-covered greenhouse in Raleigh, N.C. Infection with the soil-borne bacterial pathogen *Pseudomonas solanacearum* (Smith) Smith was anticipated from experience in preliminary studies and preplant fumigation of the sand with methyl bromide-chloropicrin (98-2) was made at 250 kg ha^{-1}. Each biofilter was inoculated with 1.0 liter of Fritz-zyme #7 (a suspension of *Nitrosomonas* Winogradsky sp. and *Nitrobacter* Winogradsky sp.), and irrigated with aquaculture effluents for nine days prior to planting the first vegetable crop. Tomato (*Lycopersicon esculentum* Mill.) or cucumber (*Cucumis sativus* L.) seedlings were transplanted into each biofilter at four plants m^{-2} in each study. Plant populations of 4, 6, 9, or 14 plants per biofilter were directly proportionate to the respective BFV.

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 (Table 2). The daily feed input rate was based on a percentage of standing fish biomass as influenced by age and mean individual weight (Pullen and Lowe~McConnell 1982). 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)

which grew in the water and on the tank sides.

Fish food was analyzed using atomic absorption spectrophotometry for K, Ca, Mg, Fe, Mn, Zn, and Cu, the vanadomolybdophosphoric yellow procedure (Jackson 1958) for P, the Kjeldahl procedure (Black et al. 1965) using a salicylic acid modification for N, a curcumin method (Grinstead and Snider 1967) for B, and a turbidanetric procedure (Hunter 1979) for S. Analyses are reported on a dry weight (DW) basis.

Irrigation water was pumped from the bottom of the fish tanks eight times daily and delivered to the biofilter surfaces at a rate of 500 L m^{-2} of biofilter surface per day. The water flooded the biofilter surfaces, percolated through the medium, and drained back to the fish tank. The tank water level dropped approximately 25 cm during each irrigation event. Therefore, the returning water provided additional aeration resulting from the effect of the cascade. Biofilters drained intensively (rapidly) for approximately 15 min. following cessation of irrigation and at a diminished rate for one hour. Evapotranspiration losses were replaced weekly with city water (McMurtry et al 1994). Input water composition and pH were reported by McMurtry (1990).

Culture water pH and temperature measurements were made in situ at random times daily with an Orion SA250 ATC pH meter using a Fisher double-junction pH electrode and Orion ATC probe. Diurnal modulation of pH, temperature, total ammoniacal-N (TAN), NO_2^-, and NO_3^- levels were assayed weekly. In the diurnal assay, the culture water of each tank was sampled prior to each filtration event, the irrigate sampled during each filtration event, and drainage from each biofilter was sampled prior to tank return. Values obtained from the random assays were compared with those taken at the same hour in the diurnal sampling of the same week. Water samples of 120 ml were drawn at the time of each water pH assay from the top of each tank, titrated to pH 2.0, sealed and stored at 5°C for up to two weeks prior to assays for nitrogenous compounds. Aqueous TAN and NO_2^- concentrations were assayed on an Orion SA270 Ion Specific Electrode

(ISE) meter using Fisher $NH_{(3+4)}$ and NO_2^-, ISE electrodes. Aqueous NO_3^- concentrations were assayed on an Orion Research Ionalyzer model 407A meter with a Fisher NO_3^- ISE electrode and were verified using a modified salicylic acid and NaOH colorimetric procedure (Cataldo et al. 1975.) with a Beckman model DB-G grating spectrophotometer. Culture tank dissolved oxygen (DO) measurements were made at 0730 and 1300 hours in situ with an Otterbine Barebo 111 DO meter at least weekly. Methyl orange alkalinity was determined by titration.

Fish biomass was determined after removal of all fish from the tank. The fish were sedated with Quinadine, blotted dry, and weighted individually. Fish biomass increase per time interval was calculated by subtraction of the respective stocked biomass. Fish were returned to the same tank with adjustments made (fish added or removed) to maintain a uniform (±2.5%) biomass between tanks. Feed conversion ratio (FCR), monthly production rate (MP), monthly specific growth rate (MSG) and the daily rate of increase in biomass (DRIB) were calculated.

The experiments were conducted as a randomized complete-block design with four replicates. Analyses of variance were made for factorial experiments with Statview™ 512+ on a personnal computer. When *F*-test(s) warranted, LSDs were calculated.

Experiment 1

Fish were stocked on 5 May 1988 at a uniform stocking density, mean individual weight (Pm_i), and initial biomass (B_i) as seen in Table 3a. An initial feeding rate of 4.3% of B_i d^{-1} was increased when inputs were consumed within 15 minutes. Daily feed input increased with fish biomass and was 2.2% of final biomass (B_f) per day at harvest 99 days from stocking. Tomato ‘Laura' was transplanted into the biofilters on 13 May 1988. This indeterminate greenhouse variety was grown as a single-stem. Fruit were harvested at the incipient color stage (McMurtry 1993b). The crop was terminated after harvest at four trusses.

Experiment 2

Fish were restocked on 25 August 1988 so that expected B_f during the succeeding interval would be lower than the 17 kg m^{-3} occurring in Experiment 1. Stocking densities, Pm_i, and B_i are given in Table 3b. A feed rate of 5.0% of B_i d^{-1} was maintained until the fish were harvested after 42 days.

The system was operated for 42 days without plants grown in the biofilters to assess whether or not olericulture was contributing to pH buffering of the water. Incremental additions of $CaMg(CO_3)_2$ were made to each biofilter after water pH fell below pH 4.0 in order to raise water pH and reestablish nitrification.

Fish biomass per tank was equalized across treatments by removing the largest individuals in appropriate tanks prior to replanting the biofilters. Feed input rate was adjusted to 3.4% of B_i d^{-1} and maintained until fish were harvested at 85 days from restocking. Cucumber 'Fidello' was transplanted into the biofilters on 22 September 1988 and pruned to a single-stem. Following $CaMg(CO_3)_2$ inputs, water pH in most tanks remained below pH 6.0 which was deemed too low for balanced nutrient assimilation by cucumber. Therefore, CaO was added to the tank water approximately twice weekly in quantities sufficient to raise water pH in each tank to above 6.5 following each application.

Experiment 3

Fish were stocked on 5 January 1989 at a uniform stocking density, Pm_i, and B_i as seen in Table 3c. An initial feed rate of 1.8% of B_i d^{-1} was reduced gradually when feed remained uneaten for more than 15 minutes. Fish were harvested 132 days from stocking. The semi-determinate, bacterial wilt-resistant tomato 'Kewalo' was planted 5 January, 1989 and grown as a single-stem (McMurtry 1993b). Fruit were harvested at the incipient color stage.

Results

Experiment 1

Mean fish growth rate (G) and the increase in total biomass increased with increasing BFV while the MSG and DRIB were not significantly different but tended to increase with BFV (Table 3a). Mean FCR tended to decrease as BFV increased. Mean individual size at harvest (Pm_f) was not different among treatments while B_f and MP differed among treatments.

Diurnal mean DO concentration increased as water temperature decreased with increasing BFV (Table 4a). Water DO concentrations ranged from 4.8 and 7.8 mg L^{-1} with minimal day to day variation (data not shown). Total alkalinity increased from 40 mg L^{-1} in week one to 180 mg L^{-1} by week five, but remained stable through week eight and was not assayed thereafter (data not shown).

The TAN and NO_2^- concentrations decreased with increasing BFV (Table 4a). Initial TAN concentrations increased from 0.0 mg L^{-1} over the first seven weeks to mean high levels ranging from 10.8 to 30.2 mg L^{-1} with decreasing BFV (data not shown). Initial NO_2^- concentrations increased from 0.0 mg L^{-1} over the first four weeks to mean high levels ranging from 3.0 to 8.1 mg L^{-1} with decreasing BFV (data not shown). At termination of the tomato crop, TAN and NO_2^- concentrations ranged from 0.7 to 1.1 mg L^{-1} and 0.02 to 0.07 mg L^{-1}, respectively (data not shown).

Mean water pH generally decreased with increasing BFV (Table 4a). Water pH increased from pH 6.5 to 7.4 in each treatment over the first 2 weeks as bacterial and plant populations became established (data not shown). Water pH declined to approximately pH 6.0 in all treatments by week 5 and remained stable through termination of the tomato crop (data not shown). Total make-up water increased with BFV and water consumption per unit biofilter area declined with increasing BFV (Table 4a). No amendments were made to adjust water pH.

Experiment 2

Water pH declined rapidly from approximately pH 6.0 in all treatments to pH 4.3 or less during the interval with no crop in the biofilters (data not shown). Subsequent $CaMg(CO_3)_2$ amendment, given in Table 4b, raised the mean pH to 5.5 or greater (data not shown).

The mean fish biomass increase ranged from 1.88 to 3.04 kg m^{-3} and G ranged 1.85 to 2.74 g $fish^{-1}$ d^{-1} at 42 days from stocking. The FCR ranged from 1.43 to 3.50, but there was no consistent trend with BFV (data not shown). The ending feed input rate was 3.1% of B_f d^{-1}.

Water pH at termination of the cucumber crop was pH 6.0, 5.5, 5.8, and 6.4 with increasing BFV, respectively (data not shown). Cucumber yield per biofilter was 11.18, 10.04, 11.41, and 33.32 kg and yield per plant was 2.80, 1.67, 1.27, and 2.38 kg with increasing BFV, respectively (data not shown). Correlation of diurnal mean pH and fruit yield per biofilter within treatments were 0.992, 0.901, 0.968, and 0.928 with increasing BFV, respectively (r^2= 0.984, 0.812, 0.937, and 0.861 with *P*= 0.008, 0.099, 0.032 and 0.072, respectively).

Feed input rate at day 85 from transplant of cucumber was 1.0% of B_f d^{-1}. Composite 127 day fish growth rates (G, MSG and DRIB) and fish biomass increase tended to increase with BFV (Table 3b). Composite 127 day FCR tended to decrease as BFV increased. Mean Pm_f did not differ between any treatment combination. The B_f and the MP rate increased with BFV through the 1:.1.50 v/v ratio

Mean water temperature generally declined with increasing BFV (Table 4b). Differences in water pH were not correlated to BFV. Total make-up water increased with BFV and water consumption per unit area declined with increasing BFV. Lime amendment was identical across treatments while CaO amendments were inversely proportional and negatively correlated to mean water pH over time (CV= -4.84, CR=

-0.82, r^2= 0.673, *P*= .0001).

Experiment 3.

The G, MSG, and DRIB rates did not differ significantly but tended to increase with BFV (Table 3c). The FCR in response to BFV was inconsistent. The fish biomass increase, B_f and MP did not differ among treatments. The feed input rate at day 77 was 0.9% of B_i d^{-1} and was 0.6% of B_f d^{-1} by the end of the 132 day feeding regime (data not shown).

The DO levels increased with BFV (Table 4c). Water DO concentrations ranged from 5.6 and 6.1 mg L^{-1} with minimal day to day variation (SD=0.31, data not shown). Water temperature decreased with increasing BFV (Table 4c).

The TAN, NO_2^- and NO_3^- concentrations decreased with increasing BFV (Table 4c). Mean NO_3^- concentrations differed between the 1: 2.25 v/v treatment ratio and each other ratio. The TAN and NO_2^- concentrations initially ranged from 0.03 to 0.20 mg L^{-1} and 0.05 to 0.10 mg L^{-1}, respectively, and increased over 2 and 10 weeks to mean high levels ranging 1.18 to 1.49 mg L^{-1} and 0.06 to 0.35 mg L^{-1}, respectively, with decreasing BFV (data not shown). At peak tomato harvest the TAN and NO_2^- concentrations ranged from 0.29 to 0.32 mg L^{-1} and 0.06 to 0.09 mg L^{-1}, respectively, with decreasing BFV (data not shown). The NO_3^- concentrations increased with BFV, initially ranged 88 to 230 mg L^{-1}, increased for 2 weeks to a range of 99 to 246 mg L^{-1}, and at peak tomato harvest had declined to 30 to 241 mg L^{-1} (data not shown).

Mean water pH tended to increase with BFV but differences were not significant because CaO inputs were made to maintain levels above pH 6.0 (Table 4c). Total make-up water increased with BFV and water consumption per unit area declined with increasing BFV. Water pH had remained low following Experiment 2 and weekly additions of CaO were made until pH remained above pH 6.0 in all treatments (data not shown). Total CaO input to each tank was negatively correlated to mean pH (CV =

-13.04, CR.= -0.86, r^2 =0.732, *P*= .0001) (Table 4c). Water pH remained stable through termination of the tomato crop following the CaO inputs (data not shown).

Total Fish Growth and Mean Water Quality in Experiments 1, 2 and 3.

The fish biomass increase in all experiments and the G, MSG, and DRIB rates increased or tended to increase with BFV (Table 5). Total fish biomass increase per plant decreased with increasing BFV while cumulative fruit yields per kg fish biomass increase increased with BFV.

The average water DO concentration increased and temperature, TAN, NO_2^-, and NO_3^- decreased with increasing BFV (Table 6). Mean water pH over time was not related to BFV. Total make-up water increased and water consumption per unit area declined with increasing BFV. Inputs of CaO were negatively correlated to diurnal mean water pH (CV.= -15.14, CR = -0.75, r^2= 0.554; *P*= 0.0009).

Water drawn from fish tanks for irrigation had TAN and NO_2^- concentrations approximately twice that of the water returning after biofiltration (Fig. 2). The percentage reduction in TAN and NO_2^- concentrations with each filtration event decreased with increasing BFV (data not shown). Percent reduction in NO_3^- concentration with each filtration event was much less than TAN or NO_2^- (data not shown).

Fish growth rates from other recirculatory systems that included olericulture were compared, contrasting similar Pm_i, Pm_f and culture intervals (Table 7). Growth rate (G) was negatively correlated to stocking density, regardless of culture system (Fig. 3). The MP per unit volume, regressed on stocking density, was found to be greater in this system (study) than in all other previous systems (studies) that had removed the suspended solid waste fraction prior to olericulture application of effluent. Mean MP from the three other culture techniques used in this comparison, adjusted to a uniform stocking density of 100 m^{-3}, would be 3.0 kg m^{-3} as compared to the treatment mean MP

of 5.8 kg m^{-3} resulting from this study.

Discussion

A rapid decline in FCR was observed in the first experiment when standing fish biomass exceeded 12 kg m^{-3} regardless of BFV. Fish were stocked in Experiments 2 and 3 so that expected B_f would not exceed 10 kg m^{-3} in order to minimize the quantity of non-ingested feed. The differential in fish weight gain between experiments is attributed to the differences in Pm_i and stocking density. Fish production in Experiments 2 and 3 was limited by a reduction in number of individuals cultured and by their relatively large P_{mf}. Growth rate (G) was similar between experiments. Because FCR declines with increasing fish size and/or age (Pullen and Lowe~McConnell, 1982), the feed input per mean standing fish biomass and per fish biomass increase was greater in Experiments 2 and 3 than in Experiment 1.

Biofiltration maintained water quality at acceptable levels for tilapia. Nitrogenous compounds, which frequently limit production in recirculatory aquaculture (Lewis et al. 1978), never reached toxic levels and were extracted by the plants (McMurtry 1990, McMurtry et al. 1993a). Yield of both fish and fruit per biofilter increased with BFV in both studies. Mean fruit yield per biofilter ranged 13.66 to 31.65 kg in Experiment 1 and ranged 19.88 to 33.11 kg with increasing BFV (McMurtry 1993b). Increased nutrient uptake by the plants with increasing yield resulted in improved water quality, and therefore, increased fish growth rates with increasing BFV (McMurtry 1993a, 1993b).

The rate of thermal energy transfer between the water and filter substrate increased with biofilter mass resulting in lower diurnal-mean water temperatures with increasing BFV. Microbial conversions and plant assimilation maintained sub-lethal concentrations of aqueous N-compounds although the assayed levels were in excess of reported toxicities of 48 h LD_{50} = 2.4 mg NH_3-N L^{-1} (Redner and Stickney 1979) and 0.45 mg

NO_2^--N L^{-1} (Balarin and Haller 1982) for tilapia. No clinical signs of nitrite toxicity were detected and the fish grew well.

Traditional recirculatory aquaculture has relied on carbonate inputs to neutralize the acidification resultant in nitrification (Rakocy 1989b). Alkaline amendment was not necessary when N input rate approximated N assimilation rates, as in Experiments 1 and 3. This was believed to be due to: 1) nitrification occurring in the biofilters where organic matter accumulated to provide buffering capacity, 2) both ammoniacal-N and NO_3^--N was available to plants, and 3) plant N uptake was mainly NO_3^- which increased alkalinity of the medium. Availability of both NH_4^+ and NO_3^- ions buffers nutrient solution pH during plant nutrient assimilation (Haynes and Goh 1978; Noggle and Fritz 1983) and NO_3^- uptake was in exchange for OH^- ions or bicarbonate ions produced during respiration (Kirkby and Hughes 1970; Riley and Barber 1971). The need for CaO amendments in Experiment 3 were considered to be due to residual acidity from Experiment 2. Once water pH was reestablished within an acceptable range for plant growth (pH 6.0-6.5), it remained stable through the conclusion of Experiment 3. Buffering of water pH also may be attributed to NH_4^+ reacting with OH^- ions released during plant anion adsorption to form NH_4OH (Noggle and Fritz 1983) or to carbonate and/or bicarbonate ions formed in the reaction of ammonia gas, CO_2 and H_2O (Berber 1968).

Comparison of growth and production levels between culture systems is complicated by Pm_i and Pm_f, stocking density, and feed quality. Good tilapia growth rates were attributed partially to water pH remaining below pH 7.0. The greatest percentage of ammoniacal-N generated in fish metabolism remains non-toxic to fish at pH levels <7.0. Fish would have reduced their feeding activity if pH had increased above pH 7.0 (Rakocy 1989a). Ammoniacal-N concentrations can be regulated by adjusting feed input rate (Rakocy 1989a). Optimum ratios between feed input rate, standing fish

biomass, system water volume, and biofilter volume needs to be established for various combinations of fish and vegetable species (Rakocy 1989b).

Uniform crop development and satisfactory performance of this system can be partially attributed to the reciprocating water movement. Muir (1982) found that high oxygen availability in the biofilter favored nitrifying bacteria over heterotrophic aerobes and starch hydrolyzers that compete for attachment sites.

This integrated food-production technique produces good yields of both fish and vegetables and reduces total production costs relative to separately operated culture systems (Rakocy 1989b; McMurtry 1990; McMurtry et al. 1994).

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