Sand Culture of Vegetables Using Recirculated Aquacultural Effluents

M.R. McMurtry, P.V. Nelson,
D.C. Sanders, and L. Hodges
Department of Horticultural Science
North Carolina State University
Raleigh, NC

Abstract. Fish production and biofiltration provided by sand-cultured vegetable crops were linked in a closed system of recirculating water. Blue tilapia (*Sarotherodon aureus* L.) were stocked as mixed-sex fingerlings at a density of 1.68 kg · m^{-3} (0.105 lb · ft^{-3}). Fish were fed a commercial chow. Greenhouse-grown bush bean (*Phaseolus vulgaris* L.), cucumber (*Cucumis sativus* L.), and tomato (*Lycopersicon esculentum* Mill.) were irrigated with water drawn from the bottom of the tilapia tank for 30 minutes every three hours during the daylight hours. Drainage from the 0.5 m (1.64 ft) deep sand beds was returned to the fish tank. Each crop was also grown in a sandy loam soil. Feeding 1 kg (2.20 lb) of fish food produced an increase of 0.76 kg (1.68 lb) fish and 1.66 kg (3.66 lb) of vegetables. Both water quality and nutrient content were adequate for tilapia and plant growth in sand culture with no supplemental fertilization. The feasibility of an integrated, recirculatory system for concurrent production of vegetables and fish with no additional fertilizer application was demonstrated.

Introduction

Benefits of integrating aquaculture and olericulture in a controlled environment include conservation of soil, water and plant nutrients, production of high-quality food products in close proximity to center of need, and reduction of operating costs. Operation of such a system is applicable wherever fish and fresh vegetables are in high demand (Hopkins, 1983).

Dissolved and suspended organic materials accumulate rapidly in aquacultural water and must be removed for efficient fish production (Nair et al., 1985). Through water purification and reuse, recirculating systems consume less than 10% of the water typically used in pond culture to produce equivalent yields of fish (Rakocy, 1989). Even in filtered recirculatory fish culture systems, nitrates and phosphates accumulate to the detriment of fish production (Balarin and Haller, 1982). Hydroponic vegetable production using recirculating aquaculture water can control nitrate concentrations (Lewis et al., 1978; Nair et al., 1985). Although many different systems of recirculating aquacultural water have been used to grow plants, typically the suspended solids are removed prior to use of the water for plant production (Bender, 1984; Lewis et al., 1978; Naegal, 1977; Nair et al., 1985; Watten and Busch, 1984). No previous studies have directly combined aquaculture water with sand-cultured plants. The purpose of this research was to determine if vegetables growing in sand beds could provide sufficient filtration of recirculated water for fish production and receive adequate mineral nutrition from only fish wastes.

Materials and Methods

A schematic view of the aquaculture-olericulture integration is seen in Figure 1. Mixed-sex fingerlings of blue tilapia (*Sarotherodon aureus* L.) were stocked at an initial density of 1.68 kg · m^{-3} (0.105 lb · ft^{-3}) in a tank with a mean volume of 22.5 m^3 (804 ft^3). Fish were fed Purina Fish Chow 5140 at 0800 and 1700 hours daily. The initial feeding rate of 3% of total fish biomass per day was reduced when feed remained for 15 minutes, with food input gradually reduced to 1% of final fish biomass per day by the end of the 86-day feeding regime (Balarin and Haller, 1982). Total feed input was 139.0 kg over the 86 day season; however, fish also grazed on algae.

Bush bean (*Phaseolus vulgaris* L. cv. Bush Blue Lake 274), cucumber (*Cucumis sativus* L. cv. Burpee Hybrid II), and tomato (*Lycopersicon esculentum* Mill. cv. Champion) were grown in a greenhouse without shading in Raleigh, NC in the summer of 1986. The crop-growing medium was a builder's grade sand composed of 98.3% quartz sand and 1.7% silt. No additional nutrients were added to the treatment beds. The sand beds were 1.5 m wide × 7.5 m long × 0.5 m deep (4.9 × 24.6 × 1.6 ft), divided into five plots, and lined with a 0.15 mm (6 mil.) polyethylene sheet to capture drainage for return to the

---

Address reprint requests to: Dr. D.C. Sanders, Department of Horticultural Science, North Carolina State University, Box 709, Raleigh, NC 27695-7609, USA.

Applied Agricultural Research Vol. 5, No. 4, pp. 280–284

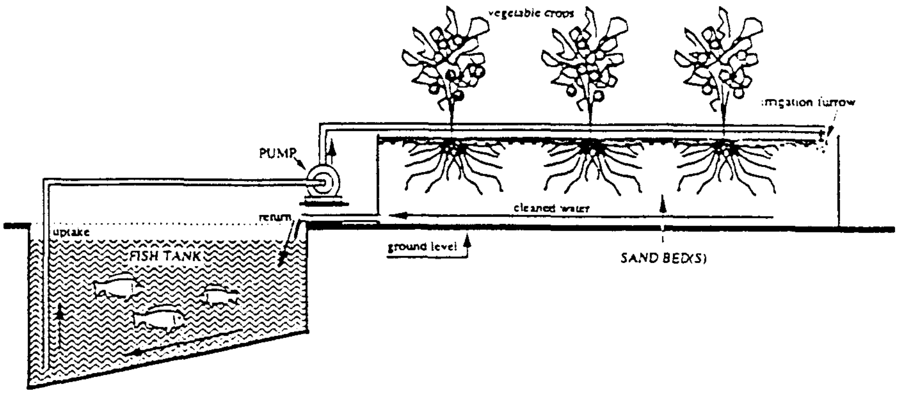

Fig. 1. Schematic of the recirculatory, integrated aquaculture/vegetable culture system.

fish tank. A single comparison system was built using a sandy loam soil amended with composted horse manure at a ratio of 5:1 (soil to manure v/v). No additional fertilizer was added to either the soil or sand beds. The soil bed [2.25 m^2 (24.2 · ft^2)] was mulched with straw and watered as needed. Bush bean and cucumber were grown in five sand plots and one soil plot. Tomato was grown in 10 sand plots and two soil plots. The tomatoes were pruned to a double-stem. Bush beans were grown at 12.5, 16.7, and 20.0 plants · m^{-2} (1.16, 1.55, and 1.86 plts · ft^{-2}); tomatoes at 1.8, 2.6, and 4.0 plants · m^{-2}, and cucumbers at 6.7 plants · m^{-2}.

Water was drawn from the bottom of the tilapia tank and pumped to the sand/vegetable beds every 3 hours during the day (5 × /day). The soil bed was irrigated with fresh well water. Water was distributed across beds in four shallow furrows. Pumping saturated the sand-bed within 5 minutes but was continued for 30 minutes to remove and distribute waste materials from the fish tank. Drainage from the beds cascaded into the fish tank increasing aeration of the pond water. Drainage continued for ≈15 minutes after pumping ceased. Dissolved oxygen was determined using a YSI Model 54 oxygen meter. Nitrite, nitrate, ammonia, and pH levels of the fish water were monitored 3 × daily with a Hach kit. Alkalinity was determined with methyl orange titration. Samples were taken from the sand medium of each plot at harvest of first mature fruit at the 0–1.6 cm (0–0.63 in.), 1.6–3.2 cm, and 3.2–4.8 cm depths with three samples from each of three distances (0.5 cm, 1.75 cm, and 3 cm) from the irrigation furrow axis for a total of 27 samples per plot (Fig. 2). A comparison sample was taken from the soil bed.

Water and media samples were analyzed using a modified Kjeldahl for total N (Bremer, 1960), ammonium molybdate-ascorbic acid colorimetric analysis for P, and K by flame emission spectrophotometry. Ca, Mg, Fe, Mn, Zn, and Cu were determined by atomic absorption spectrophotometry and a buffered ammonium chloride colorimetric analysis for S. The fourth leaf from the growing tip was collected and analyzed from each plant at the time of harvest of the first mature fruit. Plant tissue and fish food analysis was conducted using atomic absorption spectrophotometry for K, Ca, Mg, Mn, Zn, and Cu; a vanadomolybdophosphoric yellow procedure for P (Jackson, 1958); a salicylic acid modification of the Kjeldahl procedure for N (Black et al., 1965); the curcumin method for B (Grinstead and Snider, 1967); and a turbidimetric procedure for S (Hunter, 1979).

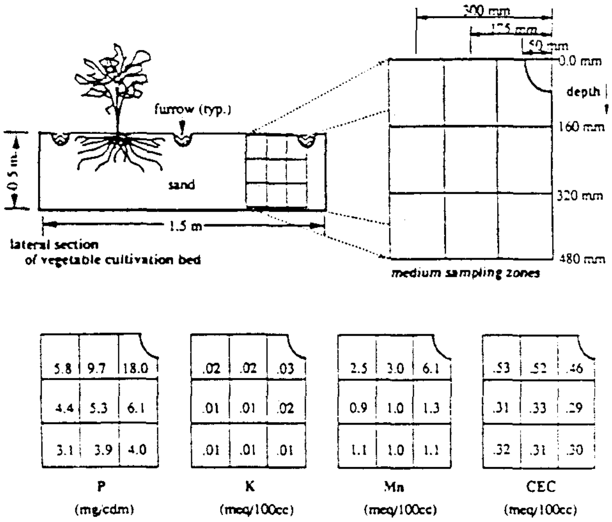

Fig. 2. Mean distribution of P, K, Mn, and CEC in the sand bed.

Results and Discussion

Total fish biomass increased from the initial 37 kg at stocking to 144 kg by the end of the 86-day feeding regime. The feed conversion ratio was 1:1.3 (76% of feed converted into fish biomass). The final average fish weight was 180 g. All-male fish cultivation could increase the yield rate three fold (Balarin and Haller, 1982). Under more intensive stocking densities, yearly fish production rates above 120 kg · m^{-3} have been attained (Armbrester, 1972).

Acceptable water quality was maintained, although dissolved oxygen was low relative to requirements for good fish growth rates (Table 1). Ni-

Table 1. Summary of aquacultural water quality

Parameter	Mean	Range
Temperature (°C)	26.9	23.0–31.0
pH	6.5	6.3–6.9
Nitrite (NO_2-N) ($mg \cdot l^{-1}$)	0.1	0.01–0.5
(NH_3 + NH_4^+)-N ($mg \cdot l^{-1}$)	0.9	0.5–1.5
Dissolved Oxygen (ppm)	2.7	0.9–7.5
Total alkalinity ($mg \cdot l^{-1}$)	20.0	10.0–40.0

Table 2. Yield of edible portion for bush bean, cucumber, and tomato from sand-bed culture and soil-bed culture

Crop	Sand ($kg\ m^{-2}$)	Soil ($kg\ m^{-2}$)
Bush bean	1.3	0.4
Cucmber	7.3	4.6
Tomato	4.6	6.1
Tomato, high-density plots		6.9

trite and ammonia, which limit the production of fish in recirculating systems (Lewis et al., 1978), never reached toxic levels.

Yield of edible portion for bush bean, cucumber, and tomato from both sand and soil beds are in Table 2. All crops developed rapidly and produced good yields despite heat stress. Integrated sand-beds produced greater yield than in conventional soil culture for beans, cucumbers and tomatoes in high density plots. Some potential tomato yield was lost due to development of bacterial wilt (*Pseudomonas solanacearum*) in the sand-cultured tomato plants.

Although the bush beans were harvested before fully mature, the yield in the soil bed was 75% of the U.S. field average for a full crop (Lorenz and Maynard, 1980). The average sand-bed bean yield was 243% of the U.S. field average. Some of this increase may have been due to edge effect of using small plots. The medium density bush bean plots (16.7 plants · m^{-2}) produced the highest yields per unit area (data not shown). The cucumber yield in the sand-beds was 111% (vs. soil = 70%) that of a typical commercial greenhouse yield. The sand-bed tomato plants set three to four times more fruit than the soil-bed plants, but these fruits aborted to excess heat. This increase in number may have been due to the improved growth resulting from a more aerated growing medium.

The soil beds had greater initial mineral content than the sand; the mineral composition of each medium did not change. Nutrient levels within 50 mm (1.97 in.) of the irrigation furrow increased when sand was irrigated with aquacultural waste water. P, K, and Mn concentrations were greatest nearest the furrow and toward surface of the bed (Fig. 2). Apparent cation exchange capacity (CEC) changes were greatest near furrows as organic matter accumulated on the surface. In general, the media concentrations of P, K, Ca, Mg, Mn, Zn, and Cu were less in the sand plots than in the soil plots (Table 3). P, K, Mn, Zn, and Cu concentrations in the sand beds also increased with proximity to the irrigation furrow.

Although nutrient levels in the recirculating water were minimal and no supplemental fertilization was added to either the sand or soil beds, plant growth was adequate due to the constant replenishment characteristic of the system (Lewis et al., 1978). The following nutrients fell below sufficiency standards but were above deficiency levels: N in all the crop species; S in the bush bean foliage; K in the cucumber foliage; and P, K, Ca, and Mg in the tomato crop (Table 4). The tomato crop had B and S levels below and at deficiency level respectively. All crops had tissue mineral contents above the minimum critical level (MCL) and there were no visual deficiency symptoms. Nutrient levels could be raised by increasing the ratio of fish biomass to crop bed area, by supplemental fertilization of the medium, and/or by foliar application of the isolated (crop-specific) element(s).

Well water was used to replace that lost through evaporation and transpiration. Makeup water requirements averaged 7.0% of the system volume per day. The pH of the water remained below 7.0 such that virtually all of the ammoniacal-N remained in ionized form (relatively nontoxic to fish). Plant assimilation of N compounds maintained nitrite and ammoniacal-N concentrations below tolerance limits for tilapia as a result of microbial nitrogen conversions occurring in the sand beds (Redner and Stickney, 1979). The water pH stability is due to the nitrate assimilation by plants counteracting the acidification from microbial nitrification in the sand beds. Additionally, the plant availability of both ammonium and nitrate ions tends to buffer the normal alkalinization of the nutrient solution occurring during plant growth (Riley and Barber, 1971). Other fish rearing systems require periodic additions of base to maintain a suitable pH (Kaiser and Wheaton, 1983; Nair et al., 1985). Reciprocating biofiltration offers the advantages of uniform distribution of nutrient-laden water within the filtration medium during the flood cycle and improved aeration in the crop medium through complete atmosphere exchange with each dewatering (Lewis et al., 1978; Nair et al., 1985; Paller and Lewis, 1982). These advantages benefit both the nitrifying bacteria and the plant roots

Table 3. Nutrient content of plant production medium prior to irrigation and at date of first mature fruit in the soil-bed system and the sand-bed system

Treatment[a]	CEC (meq)[c]	P (mg · dm^{-3})	K (meq)[c]	Ca (meq)[c]	Mg (meq)[c]	H_+ (pH)	Mn (mg · dm^{-3})	Zn (mg · dm^{-3})	Cu (mg · dm^{-3})	BS[b] (%)
Prior to irrigation										
Soil bed	8.7	199 +	0.72	6.8	0.75	6.30	36.0	19.0	6.60	89
Sand bed	0.5	6	3.90	0.1	0.07	5.30	2.1	1.2	0.30	100
At first mature fruit										
Bush bean										
Soil Mean	5.71	255	0.77	4.0	0.79	6.40	42.00	13.5	7.7	88
SD	3.00	130	0.49	2.0	0.54	0.83	16.80	4.7	4.3	14
Sand Mean	0.24	4.4	0.01	0.2	0.07	5.65	1.06	1.1	0.6	100
Next to furrow	0.12	5.6	0.02	0.2	0.09	5.94	2.16	2.5	0.9	100
SD	0.08	0.8	0.01	0.0	0.02	0.20	0.81	0.9	0.3	0
Cucumber										
Soil Mean	7.37	313	0.87	5.6	0.94	5.78	42.0	20.0	6.9	93
SD	2.51	92.0	0.49	1.8	0.40	0.33	9.6	11.0	3.7	3
Sand Mean	0.30	3.6	0.01	0.2	0.10	5.85	1.9	1.8	0.7	73
Next to furrow	0.43	10.0	0.02	0.3	0.10	6.29	5.1	4.9	1.3	85
SD	0.08	4.3	0.01	0.1	0.10	0.26	1.7	1.5	0.3	13
Tomato										
Soil Mean	6.43	270	0.60	0.5	0.93	6.47	42.4	10.2	3.4	89
SD	2.33	90.0	0.26	1.6	0.54	0.54	10.9	3.7	0.8	7
Sand Mean	0.40	9.4	0.02	0.3	0.11	6.03	2.6	1.5	4.7	94
Next to furrow	0.36	8.5	0.03	0.3	0.09	6.27	5.6	3.6	1.1	100
SD	0.25	17.0	0.02	0.2	0.22	0.41	3.3	1.3	2.2	11

[a] Sand refers to integrated aquaculture-vegetable system incorporating a sand-culture bed; soil indicates a loamy sand soil-bed system irrigated with well water; Sd = standard deviation. Values are the mean of 135 samples per bed. "Next to furrow" = data mean of sample values from top 160 mm from furrow axis.

[b] BS = base saturation

[c] Milliequivalents (meq) per 100 cubic centimeters.

Table 4. Foliar tissue analysis of bush bean, cucumber, and tomato at date of first mature fruit as in the soil-bed system and in the sand-bed system

Crop	Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (ppm)	Mn (ppm)	Zn (ppm)	Cu (ppm)	S (ppm)	B (ppm)
Bean	Sufficiency[a]	5.00	0.30	2.25	1.50	0.30	50	20	20	5	2000	20
	Soil-bed	3.89	0.46	7.15	1.32	0.41	119	30	40	12	1632	24
	Sand-bed (mean)	4.22	0.39	3.32	2.70	0.64	146	104	139	15	1692	15
	Sand-bed (SD)[b]	0.12	0.05	0.31	0.54	0.09	67	24	51	2	154	4
	Deficiency[c]	<3.50	<0.20	<1.25	<0.30	<0.15	<30	<15	<15	<3	<1500	<15
Cucumber	Sufficiency	6.00	0.30	4.00	1.50	0.25	45	30	20	5	2000	25
	Soil-bed	5.39	0.64	5.24	2.64	0.63	111	33	63	14	3521	26
	Sand-bed (mean)	4.64	0.47	3.07	2.15	0.71	98	103	186	14	2204	20
	Sand-bed (SD)	0.52	0.12	1.46	0.35	0.07	9	47	82	1	884	4
	Deficiency	<4.00	<0.20	<2.00	<0.75	<0.15	<30	<20	<15	<3	<1500	<15
Tomato	Sufficiency	3.50	0.35	3.50	1.00	0.30	45	30	20	5	3000	30
	Soil-bed (mean)	3.61	0.56	4.03	0.98	0.32	94	30	25	14	3035	28
	Sand-bed (mean)	3.16	0.35	3.11	0.94	0.28	67	58	49	17	936	15
	Sand-bed (SD)	0.34	0.09	0.26	0.25	0.03	9	13	16	26	197	1
	Deficiency	<2.50	<0.18	<2.00	<0.50	<0.20	<25	<20	<15	<3	<1500	<15

[a] Sufficiency guidelines for field and greenhouse crops provided by the North Carolina Department of Agriculture.

[b] SD = standard deviation. Values are based on five samples per bed.

[c] Deficiency guidelines for the respective crop by the North Carolina Department of Agriculture.

(Hopkins et al., 1950; Paller and Lewis, 1982). Uniform crop development and satisfactory performance of this system are due to the reciprocating water movement, which resulted in even distribution of nutrients and O_2 to plants during the drainage period. The plant-sand filtration system maintained water quality resulting in good fish weight gain and vegetable crop production. The feasibility of the integration of aquaculture using sand and crop plants to maintain water quality and promote fish growth was shown. The potential for increased fish biomass:vegetable production ratios enhances the economic feasibility of the system. More detailed investigations into the biological interactions and economic potential of this system are presently being conducted.

Acknowledgment. The authors gratefully acknowledge the assistance of R.L. Noble, B. Noon, R.P. Patterson, S. Pulver, J. Riddle, and R. Tucker for their help on the project. This project was designed and tested by the senior author in partial fulfillment of the Master of Product Design. Mention of a trademark, proprietary product, or vendor does not imply its approval to the exclusion of other products or vendors that also may be suitable.

References

Armbrester, W. 1972. The growth of caged *Tilapia aureus* (Steind.) in fertile farm ponds. Proc. Ann. Conf. Southeastern Assoc. Game Fish Comm. 25:446–451.

Balarin, J.D., and R.D. Haller. 1982. The intensive culture of tilapia in tanks, raceways and cages. P. 266–356. *In:* Muir, J.F. and R.J. Roberts (eds.) Recent advances in aquaculture. Westview Press, Boulder, CO.

Bender, J. 1984. An integrated system of aquaculture, vegetable production and solar heating in an urban environment. Aquacultural Eng. 3:141–152.

Black, C.A., D.D. Evans, J.L. White, L.E. Emsminger, and F.E. Clark. 1965. Methods of soil analysis. Part 2: Chemical and microbiological properties. Amer. Soc. Agron., Madison, WI.

Bremer, J.M. 1960. Determination of nitrogen in soil by the Kjeldahl method. J. Agric. Sci. 55:11–33.

Grinstead, R.R., and J. Snider. 1967. Modification of the curcumin method for low level boron determination. Analyst 92:532–533.

Hopkins, K.D. 1983. Tilapia culture in arid lands. International Center for Living Aquatic Resource Management, Manila, Philippines. ICLARM Newsletter 1.

Hopkins, H.T., A.W. Specht, and S.B. Hendricks. 1950. Growth and nutrient accumulation as controlled by oxygen supply to plant roots. Plant Physiol. 25:193–208.

Hunter, A.N. 1979. Custom Laboratory Equipment, Inc. P.O. 757, Orange City, FL 32763.

Jackson, M.L. 1958. Soil clinical analysis. Prentice-Hall, Inc., Englewood Cliffs, NJ, p. 151–154.

Kaiser, G.E., and F.W. Wheaton. 1983. Nitrification filters for aquatic culture systems: state of the art. J. World Maricult. Soc. 14:302–324.

Lewis, W.M., J.H. Yopp, H.L. Schramm, and A.M. Brandenburg. 1978. Use of hydroponics to maintain quality of recirculated water in a fish culture system. Trans. Amer. Fisheries Soc. 107:92–99.

Lorenz, O.A., and D.N. Maynard. 1980. Knott's handbook for vegetable growers. 2nd ed. John Wiley & Sons, New York.

Naegal, L.C.N. 1977. Combined production of fish and plants in recirculating water. Aquaculture 10:17–24.

Nair, A., J.E. Rakocy, and J.A. Hargreaves. 1985. Water quality characteristics of a closed recirculating system for tilapia culture and tomato hydroponics. p. 223–254. Proc. Second International Conf. on Warm Water Aquaculture, Hawaii.

Paller, M.H., and W.M. Lewis. 1982. Reciprocating biofilter for water reuse in aquaculture. Aquacultural Eng. 1:139–151.

Rakocy, J.E. 1989. A recirculating system for tilapia culture and vegetable hydroponics in the Caribbean. Proc. Auburn Symposium on Fisheries and Aquacultures, Sept. 20–22, 1984. Brown Publishing Co., Montgomery, AL.

Redner, B.D., and R.R. Strickney. 1979. Acclimation to ammonia by *Tilapia aureus*. Trans. Amer. Fish. Soc. 108:383–388.

Riley, D., and S.A. Barber. 1971. Effect of ammonium and nitrate fertilization on phosphorus uptake as related to root-induced pH changes at the root-soil interface. Soil Sci. Am. Proc. 35:301–306.

Watten, B.J., and R.L. Busch. 1984. Tropical production of tilapia (*Sarotherodon aureus*) and tomatoes (*Lycopersicon esculentum*) in a small-scale recirculating water system. Aquaculture 41:271–283.