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Use of Hydroponics to Maintain Quality of Recirculated Water in a Fish Culture System[1]

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ABSTRACT

Fish production, biofiltration, and hydroponics were linked in a closed system of recirculating water. Fish tanks were stocked with channel catfish (*Ictalurus punctatus*) and the fish were fed daily. A revolving plate-type biofilter was used. Three field varieties of tomatoes (*Lycopericon esculentum*) were planted in outdoor hydroponic tanks. Three production units were operated during the 1976 growing season. All significant water quality variables were monitored. Performance was evaluated in terms of water quality, vegetative and fruit production of the tomatoes, and growth of the fish. Fish survival was high, but growth was below maximum because the temperature in the system was below optimum. The average loading rate of fish for the three units at harvest was 31.5 kg/unit, 489 g/tomato plant, 1.9 kg/m^2 of hydroponic area, and 691 g/m^2 of biofilter surface. Excellent water quality was maintained. The biofilter satisfactorily converted the waste to nitrate-N and phosphate-P and the hydroponic system removed these end products from the water. Nutrients were periodically added to supplement the nutrients from fish waste. Tomato yield was approximately twice that either demonstrated or expected in field production of the same varieties, and the hydroponically produced tomatoes were of better quality than the same varieties grown under field conditions.

Biofiltration is being used in recirculating-water systems to produce salmonids (Burrows and Combs 1968), and it appears appears practical for cool and warmwater tank culture (Lewis and Buynak 1976). In fish production systems based on recirculated water and involving biofiltration, the accumulation of the end products, nitrate-N and phosphate-P, is controlled by partial flush, or as recommended by Meade (1974), by denitrification. In the present study we have examined the use of hydroponics as a means of preventing the accumulation of nitrate-N and phosphate-P, while at the same time producing tomatoes as a marketable by-product. Sneed et al. (1975) examined the hydroponic culture of various plants in the effluent from catfish holding tanks. Their system was quite different from the one considered here, inasmuch as theirs was a single-pass system and did not involve biofiltration.

METHODS

To evaluate the efficiency of hydroponics in preventing the accumulation of nitrate-N and phosphate-P, we designed a system based on recirculated water (Figs. 1, 2). The facility consisted of three identical units, each of which included a fiberglass fish culture tank, a reservoir, a biofilter, and two hydroponic tanks. Each fish culture tank, which at operating water level contained 870 liters of water, was equipped with an agitator for aeration and an automatic fish feeder patterned after Wehr and Lewis (1974). The tanks were coupled to revolving plate biofilters modeled after Lewis and Buynak (1976). Each biofilter consisted of three components, each having 30 corrugated fiberglass plates (52-cm diameter) for a total surface area of 45.6 m^2. The plates were mounted on a 2.5-cm shaft supported by bearings on each end so that slightly less than one half of each plate was submerged. The plates were rotated at 6 rpm by a fractional horsepower gearmotor. The biofilter was connected to a settling tank that consisted of a 200-liter drum with a water inlet 25 cm above the bottom and an outlet 18 cm below the top. The design was such that most of the solids settled below the inlet or floated above the outlet. The settling tank was connected to a perforated pipe extending the length of each of the two hydroponic tanks.

The hydroponic tanks were built of con-

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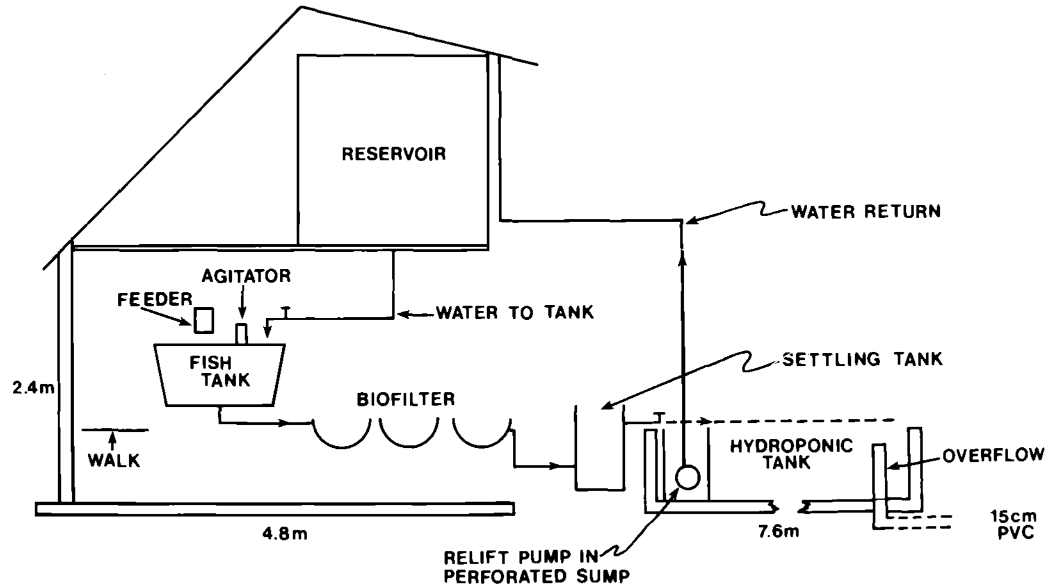

FIGURE 1.—*A system combining fish production tanks and hydroponic tanks (elevation).*

crete blocks and were 7.6 m long × 1.2 m wide × 0.75 m deep. The concrete blocks were filled with concrete except where plastic pipes had been placed to serve as insertion holes for 1.5-m long wooden stakes that were used to provide support for the tomato plants. The interior of the tanks was painted with an epoxy resin, lined with polyethylene, and filled with river gravel as follows: a 10-cm bottom layer of 38–50-cm size, a 10-cm layer of 12–25-cm size, and a 45-cm top layer of 5–10-cm size. At one end of each tank was a 15-cm removable standpipe that served the dual function of an overflow, or when removed, a drain. At the other end of each hydroponic tank was a sump for the relift pump. This sump was made by removing both ends from a 200-liter steel drum, perforating the sides, and setting it in concrete.

Located above the fish culture tank was a reservoir having a capacity of 3,800 liters. Water was gravity-fed from this reservoir to the fish culture tank at a rate of 10 liters/minute. From the fish culture tank the water flowed through the biofilters, from the biofilters to the settling tank, and from the settling tank through the perforated pipes placed along the surface of the two hydroponic tanks. The water accumulated in the hydroponic tanks until it reached a level just below the surface of the gravel, at which point a 110-volt float switch activated a 220-volt relay which energized the relift pump in the respective tank. In about 10 minutes the pump drained the hydroponic tank, returning the water to the reservoir. The result of this flow pattern was alternately to fill and drain the hydroponic tanks approximately every 2 hours. The total volume of each system, including the reservoirs, was 3,850 liters. The experimental design provided for the addition of enough makeup water to maintain operating level in the system. Because of leakage from the hydroponic tanks more water was added than was lost by evaporation and transpiration. The amount of makeup water added was 6.6% of the total volume per day. Water used for makeup was aerated well water having the following characteristics: PO_4-P, 0.04 ppm; NO_3-N, 1.8 ppm; NO_2-N, 0.0 ppm; NH_3-N, 0.4 ppm; methyl orange alkalinity, 231 ppm (as $CaCO_3$); dissolved oxygen 3.4 ppm; pH, 8.1.

Yearling channel catfish (*Ictalurus punctatus*), averaging 112 g, were stocked at a density of 60 fish in each of the three culture tanks on 10 May 1976. On 10 July approximately 50 fish, averaging 100 g, were

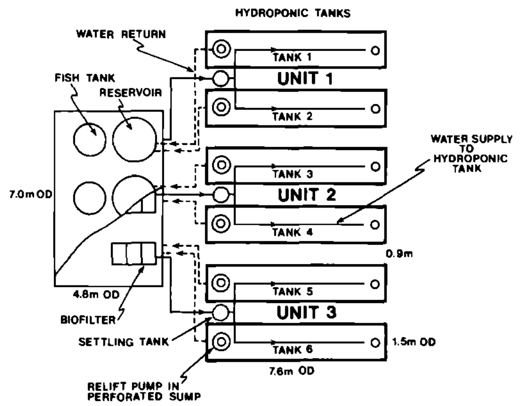

FIGURE 2.—*A system combining fish production tanks and hydroponic tanks (plan).*

added to each tank. The fish were fed Purina Trout Chow at a rate of 2% of their body weight per day.

On 27 May three varieties of tomato (*Lycopericon esculentum*) seedlings were planted in the hydroponic tanks. Preliminary screening of twelve popular table, canning, and tomato paste varieties during late winter, according to performance in circulating nutrient solution, led to the choice of Floradel and Campbells 1327 for canning and table varieties and San Marzano for tomato paste variety. In addition, the two canning varieties represent different growing types. Floradel is an indeterminate variety and Campbells 1327 is determinate. Treated, pure seed stock from a local seed company was used to obtain seedlings by greenhouse culture. The plants had been started in the greenhouse on 25 March in sterilized wooden flats containing Pro-Mix B (manufactured by Premier Peat Moss Corp., New York, N.Y.) potting soil. They were hardened by exposure to field conditions every day for one month before being transplanted to the hydroponic tanks. Immediately before planting, each plant was washed completely free of its potting soil. Plant height at the time of planting was 20–25 cm for all three varieties. Two rows of 16 seedlings were planted in each unit. The plants were 23 cm from each end and 30 cm from the sides. The two rows were 60 cm apart and the plants were 46 cm apart in the rows. Tomato twine was tied to the wooden stakes at the 1-m height in a manner providing a series of rectangular supports crossed diagonally over the tanks. Plants were supported by means of twine tied to the diagonal frames and the third set of branches. No other support was provided. Tomato variety distribution was: Tanks 1 and 6, Floradel; Tanks 2 and 4, Campbells 1327; and Tanks 3 and 5, San Marzano. The axillary buds (suckers) of the first branches were removed from the tomato plants in mid-June.

While the principal source of nutrients for the plants was the fish waste, chemical monitoring of the major nutrient elements served as a guide for periodic additions of supplemental plant food nutrients. The balanced nutrient regime was calculated to achieve a low level of all essential elements (Asher and Ozanne 1967). The use of minimum nutrient levels was possible because of the constant replenishment characteristic of a system based on recirculated water. The elements added and the concentrations of each are given in Table 1.

Day-to-day monitoring included observation for fish mortality and for symptoms of nutrient deficiency and disease in the tomato plants. Makeup water was added and ripe tomatoes were harvested daily. Twice each week water quality variables were measured at critical points in the system. Dissolved oxygen was determined by a YSI Model 54 oxygen meter. Nitrogenous compounds were originally measured with an Orion 801A ion-analyzer; however, after 26 July, because of malfunctions of the nitrite and nitrate electrodes, these analyses were made with a Hach Kit. Use of the ion-analyzer was continued for the measurement of ammonia. Once each week methyl orange alkalinity was determined by titration and pH was measured with a Corning Model 12 pH meter; available phosphorus was measured using the ascorbic acid method (APHA et al. 1971); and metal ion concentrations were determined with a Beckman Model 1301 atomic absorption unit. Periodic measurements of temperature stratification within the hydroponic tanks were made with a YSI Model 44-TA telethermometer.

TABLE 1.—*Balancing nutrients periodically added to hydroponic units in which fish waste was the primary nutrient source.*

Element	Concentration of element at time of addition (mg/liter)	(μM)	Chemical source of element	Total of element added during study (g/unit)
N	33.600	2,400	$NaNO_3$	263.0
Ca	40.100	1,000	$CaCl_2 \cdot 6H_2O$	952.0
Mg	9.700	400	$MgSO_4 \cdot 7H_2O$	345.0
P	6.200	200	Na_2HPO_4	331.2
S	6.400	200	$MgSO_4 \cdot 7H_2O$	227.0
K	3.900	100	KCl	187.2
Cl	354.600		KCl and $CaCl_2$	
B	0.140	13	H_3BO_3	4.15
Fe	0.500	9	$FeSO_4 \cdot 7H_2O$ and Fe EDTA	17.8
Mn	0.270	5	$MnSO_4 \cdot 2H_2O$	8.0
Zn	0.130	2	$ZnSO_4 \cdot 7H_2O$	3.8
Cu	0.030	0.5	$CuSO_4 \cdot 5H_2O$	0.9
Mo	0.009	0.1	$NaMoO_4 \cdot 2H_2O$	0.3

Growth rates of the fish were determined twice during the experiment by taking a sample of 20 fish, weighing them individually, and returning them to the system. Tomatoes were evaluated by determining the production of vegetative growth, fruit production, and quality of fruit. The parameters of quality considered were consistent with U.S. Department of Agriculture standards given by Gould (1974). After the final tomato harvest on 18 September, fresh weight and length of all tomato plants were recorded. The fish were harvested on 4 October and total length and weight of the individual fish were recorded.

RESULTS

The maximum loading rate of fish was at harvest, when average loading rate was 31.5 kg/unit, 489 g/tomato plant, 1.9 kg/m^2 of hydroponic area, and 691 g/m^2 of biofilter surface area (Table 2). At this loading rate the water quality remained high. This was achieved by biofiltration of the waste water, removal of nutrients by the tomato plants, and the addition of 6.6% makeup water daily. Except for water temperature, the physiochemical parameters were within the ranges amenable to maximum growth of catfish.

Dissolved oxygen concentration in the fish culture tank influent averaged 7.1 ppm (83% saturation), and never fell below 5.4 ppm. Effluent from the tanks averaged 6.5 ppm

TABLE 2.—*Loading rate of channel catfish in a recirculated water system involving fish culture tanks, biofilters, and hydroponic tanks.*

Date and event	Unit	Weight per unit (g)	Weight per tomato plant (g)	Weight per hydroponic area (g/m^2)	Weight per biofilter surface (g/m^2)
10 May, 1st stocking	1	6,720	105.0	371.3	147.4
	2	6,720	105.0	371.3	147.4
	3	6,720	105.0	371.3	147.4
10 July, 2nd stocking	1	16,600	259.3	917.1	364.0
	2	16,200	253.1	895.0	355.3
	3	16,500	278.8	911.6	361.8
4 October, harvest	1	31,755	496.2	1,754.4	696.4
	2	33,940	530.3	1,875.1	744.3
	3	28,935	452.1	1,598.6	634.5

(76% saturation). The concentration in the hydroponic tank effluent averaged 4.8 ppm (57% saturation).

Water temperature was less than expected and less than that required for maximum growth of catfish. The temperature in the fish culture tanks averaged only 23 C from 14 May to 18 September. During the period of highest temperature (14 days in July) the range was 25–27 C. The top 6 cm of gravel in the hydroponic tanks constituted an effective barrier to the transmission of the high surface temperatures reached during midsummer. At no time during the growing season were the tomato roots subjected to a temperature more than 3 C higher than that of the influent water.

Methyl orange alkalinity averaged 227 ppm (as $CaCO_3$) during the study. This level of alkalinity produced well-buffered water and, as a consequence, fluctuations in pH were small (7.7–8.3).

Concentrations of metal ions had a wide range. Potassium, magnesium, and calcium concentrations in the hydroponic tank influent ranged from 3.0 to 18.0 ppm, 19 to 41 ppm, and 25 to 60 ppm, respectively. In the effluent the potassium, magnesium, and calcium concentration ranges were 2.5 to 27.0 ppm, 12.0 to 36.0 ppm, and 26.0 to 49.0 ppm. The variation is a consequence of the objective of keeping mineral ions at their lowest level above threshold for plant uptake. The minerals were added at levels calculated to permit above-threshold values for at least 1 week of active plant uptake.

Nitrogenous compounds, which frequently limit the production of fish in systems supplied by recirculated water, never reached levels toxic to the channel catfish. Nitrite-N attained concentrations as high as 0.5 ppm in the fish culture tank influent, but were usually in the order of 0.13 ppm. After the addition of nitrates in nutrient packages to achieve threshold levels for the tomatoes, NO_3-N concentrations reached 40 ppm, but under normal conditions values were between 6 and 10 ppm.

The revolving plate biofilters were effective in converting ammonia-N to nitrate-N. During the period in which fish growth was the greatest (10–30 July), total ammonia-N (NH_3 + NH_4-N) concentrations in the biofilter influent ranged from 0.056 to 0.95 ppm. In every instance the total ammonia concentration was substantially reduced by biofiltration.

During the period 26 July to 13 September average NO_3-N concentration in the effluents of the biofilters were: Unit 1, 6.39 ppm; Unit 2, 6.43 ppm; Unit 3, 5.72 ppm. Average concentrations over the same period in the effluents of hydroponic tanks 1 through 6 were 5.41, 5.45, 5.39, 5.16, 4.99, and 5.42, respectively. Thus the percentage removals were: 15.3, 14.7, 17.7, 19.8, 12.8, and 5.2. Since the hydroponic tanks each contained 600 liters when filled, the average total amount of NO_3-N removed per turnover was 588, 564, 684, 762, 438, and 180 mg.

The phosphate-P concentrations were less than those of nitrate-N, but the percentage removals by the tomato plants were comparable. The influent to hydroponic tanks 1 through 6 had concentrations of 1.57, 1.57, 1.38, 1.38, 1.55, and 1.55 (values are duplicate because of the common source of water). For these tanks the concentrations in the effluents were 1.28, 1.27, 1.30, 1.29, 1.22, and 1.13 ppm. The percentage removals were 18.5, 19.1, 5.8, 6.5, 14.8, and 24.0. The total amounts of phosphate-P removed during a turnover period were 174, 180, 48, 54, 138, and 222 mg.

From 10 May to 10 July, at a mean water temperature of 21 C, the average weight gain for fish in the three tanks was 1.26 g/day/fish. From 10 July to 30 July, at a mean temperature of 25 C, the average gain in the three tanks was 3.63 g/day/fish for fish of the first stocking. Fish of the second stocking (10 July) gained an average of 2.10 g/day/fish during the same period. From 30 July to 28 August, when it was no longer possible to distinguish between fish of the first and second stockings, and at a mean temperature of 21 C, the average gain for the three tanks was 2.05 g/day/fish. The weight frequency distributions yielded a coefficient of variation of 0.33, 0.29, and 0.30, respectively, for populations in the three fish culture tanks. The number of fish which attained marketable size (450 g or more) was 4%, 2%, and 10% respectively. Mortalities were: 7%, 1.5%, and 2.1% for Units 1, 2, and 3 respectively. The principal cause of mortality was from fish jumping out of the tanks.

The spring and early summer of 1976 were exceptionally cool, resulting in slow tomato growth from 27 May to 17 June. Thereafter, the tomatoes grew rapidly and produced strong, healthy plants which were dark green, fully turgid, and disease-free. The only deficiency exhibited was that of iron, which was evident in all three varieties on 25 July. This was believed to be due to relatively high pH of the water and was corrected by the addition of chelated iron (ethylene diamine tetra-acetic acid). The deficiency disappeared within 1 week.

The total biomass yield (dry weight of tomatoes plus plants) per hydroponic unit (two tanks containing different varieties) was within 10% of each of the other two units. The yields were: Unit 1, 27,723 g;

TABLE 3.—*Vegetative growth and fruit of tomatoes produced in a hydroponic system with fish waste as the principal source of plant nutrients.*

Unit	Tank number	Fresh weight of plants (g)	Dry weight of plants (g)	Fresh weight of tomatoes (g)	Dry weight of tomatoes (g)
1	1	59,979	7,869	161,243	7,918
	2	39,460	5,359	140,605	6,577
	Total	99,439	13,228	301,848	14,495
2	3	44,955	4,954	152,565	7,782
	4	39,980	5,429	151,742	7,113
	Total	84,935	10,383	304,307	14,895
3	5	47,100	5,190	139,060	7,050
	6	40,100	5,261	183,395	8,996
	Total	87,200	10,451	322,455	16,046

Unit 2, 25,278 g; and Unit 3, 26,497 g (Table 3). The principal reason for even this slight variation was the superior yield of the variety Floradel (tanks number 1 and 6). Both plant yield and tomato fruit yield of this variety were more than 16% higher than the other two varieties.

Fruit yield was excellent for all three varieties. Yield per plant for all varieties was more than 4.6 kg. Floradel was the heaviest yielder of ripe and green tomatoes (green tomatoes were picked only at the time of final harvest). The fresh weight of ripe tomatoes for Floradel, Campbells 1327, and San Marzano was 268, 249, and 242 kg, respectively. Again, plants of Floradel had the greatest weight of green tomatoes, followed by San Marzano and Campbells 1327.

Picking of all three varieties began in the third week of July. The maximum yield for all varieties was in the second week of August. Fruit quality was consistently high. The percentage of number one graded tomatoes for each variety was: Floradel, 76; San Marzano, 72; and Campbells, 60. Except for one picking in the third week of August, cracking around the stems was less than 4% for Floradel and San Marzano, and less than 10% for Campbells. Color development was uniform, and the fruits were both large and uniform in size. The average fresh weight of ripe fruit for Floradel, Campbells, and San Marzano was 285 g, 245 g, and 80 g, respectively. Keeping quality of ripe fruit was very good for all varieties. Tomatoes retained turgor and color after being stored for more than 3 weeks at 6 C.

DISCUSSION

Dissolved oxygen remained at a high level throughout the system, which indicated that the system was not overloaded and that the biofilters and sedimentation tanks were functioning properly. Water temperature was lower than had been anticipated, and for much of the season was below the range (28–30 C) for maximum growth of channel catfish. The exceptionally cool spring and summer experienced in 1976 accounted in part for the low water temperature, and temperature was further decreased by evaporation from the biofilters. The problem of less than maximum growth of catfish might be corrected by supplemental heat in the fish culture tanks, selecting a strain of catfish that exhibits maximum growth at a lower temperature range, or identifying another species of fish better suited to cool water. In any event, catfish growth in such a system should prove to be more satisfactory in a warmer climate.

The high methyl orange alkalinity (227 ppm $CaCO_3$), as well as the addition of 6.6% makeup water, prevented the system from becoming acid, a situation which often leads to a buildup of nitrites. The average pH of the hydroponic culture (about 8.0) was above that generally accepted as optimal for tomato growth (5.5 to 7.0). But despite the high pH, the growth and production of tomatoes was good. The reason for this may be that under most soil conditions, micronutrients (especially iron) are precipitated and mineral ions bond to charged soil particles. In our hydroponic system the chelating agent ethylene diamine tetra-acetate was present. Further, there is a difference between the occurrence of particles of high charge density in soil as compared to the hydroponic system. The system thus permitted the benefit of high chemical buffering without the deleterious effects that occur in soil culture.

The high levels of calcium and magnesium, which resulted in part from the makeup water, were much above threshold requirements for the tomatoes. These ions, while contributing to the methyl orange alkalinity, were responsible for the high buffering capacity of the system. Potassium was monitored, however, to insure that above-threshold levels could be achieved by periodic addition.

Because of their toxicity to fish and the large quantities required for plant growth, the nitrogenous compounds are of particular interest. Nitrite-N values (high 0.5 ppm, average 0.13 ppm) were well below the 96-hour mean tolerance limit of 7.5 ppm (reported as 24.6 mg/liter nitrite) established by Konikoff (1975).

The effects of molecular ammonia on fish range from suppression of growth and gill damage to mortality. Molecular ammonia-N values in the fish tank influent rarely exceeded 0.0014 ppm. The level in the effluent from the fish tanks at one time was 0.123 ppm, but was typically in the range of 0.015 to 0.005 ppm. Robinette (1976) established that sublethal effects of molecular ammonia occur at 0.12 ppm NH_3-N. Thus ammonia remained below the lethal level, and the discharge water from the tanks only once approached that which causes sublethal effects. The nitrate-N values (maximum 40 ppm, average 6–10 ppm) were well below the tolerance limit of fish (above 80 ppm).

The present research evaluated a recirculation system in which the principal concern was to insure that nitrogenous compounds remained below the level toxic to fish. However, the biofilter/hydroponic system has a different application in connection with single-pass fish culture systems, where the objective is to reduce the waste products to a level permissible for discharge. Of particular concern are the levels of nitrogenous compounds and phosphorus. The National Technical Advisory Committee (1968) set permissible levels for ammonia-N at 0.5 mg/liter, and nitrite + nitrate-N at 10 mg/liter. It appears possible that hydroponics can be used to attain these standards in single-pass systems as well as in recirculation systems; however, this question requires further examination.

The biological success of the system examined in the present work was in part related to certain design features. The revolving plate biofilter was self-cleaning, trouble-free, and gave a uniform breakdown of the complex organics. The elevated reservoirs allowed the water to flow by gravity into the fish tanks, providing several hours of protection during periods of power outage. The uniform growth of tomatoes and the satisfactory performance of the hydroponic system can in part be attributed to the reciprocating type of water movement that insured even distribution of nutrients and oxygen to all plants, as well as drawing atmospheric oxygen into the gravel bed during the dewatering period. The temperature difference between the environment of the shoots and that of the roots of the tomato plants was probably beneficial to plant growth and may have promoted continual fruit set. Also essential to the success of the system was the protection of water from sunlight, which prevented algal growth from taking up the nutrients.

The coefficient of variation of the weight frequency distribution in the three fish populations is the same as that obtained by Konikoff and Lewis (1974) for three populations of caged catfish where the fish were initially selected for uniformity of size. This indicates that the variation in growth produced under the conditions of the culture system used in this study was normal.

The temperature for maximum growth of channel catfish is between 28 and 30 C (Andrews et al. 1972). The temperature in the present system never reached this level. During the period of highest temperature for which specific growth rate is available (10–20 July), the average gain for the three tanks was 3.63 g/day/fish. At this growth rate, beginning with a 50-g yearling, it would require 111 days to produce a minimum marketable-sized fish (450 g). The mean value of 2.05 g/day/fish was obtained at 21 C. Again beginning with a 50-g yearling, it would require approximately 191 days to produce a 450-g fish. Inasmuch as temperature control is reasonably practical for a recirculation system, it appears that it would be beneficial to maintain temperature at a level which would permit maximum growth.

This hydroponic system is outdoors, compared to most units which are in greenhouses. The tomatoes produced in this system were not greenhouse varieties (although Floradel may also be used for this purpose), but rather were those which are grown as commercial field crops, selected by preliminary screening for their suitability to hydroponic culture. The yield per plant for Campbells 1327 in the hydroponic system was 4.6 kg, as compared to 2.7 kg per plant reported for 1976 field trials at the University of Kentucky (C. R. Roberts, personal communication). The yield for the other two varieties grown hydroponically was approximately twice that which would be expected under field conditions. The weight of green tomatoes at harvest indicates that a greater yield would be possible if harvest were delayed for two weeks. The superior yield of the Floradel variety probably reflects its indeterminate nature. However, Campbells 1327, despite its determinate growth habit, continued to bloom and set green fruit even in mid-September. This might be attributed to the maintenance of excellent growing conditions and uniform nutrient supply as a consequence of the hydroponic culture. Fruit quality determined by U.S. Department of Agriculture grading standards indicates that the hydroponically produced tomatoes were superior in quality to the same varieties produced under field conditions, particularly late in the season.

It is of interest that the only parasite or disease problem encountered was hornworm, and the use of pesticides and herbicides was not required. It is understandable that weeds and pests dependent upon soil for part of their life cycle would not be troublesome in the hydroponic system. To the extent that the occurrence of parasites and diseases is reduced, and the use of pesticides and herbicides correspondingly curtailed, the end product would be more attractive to consumers.

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