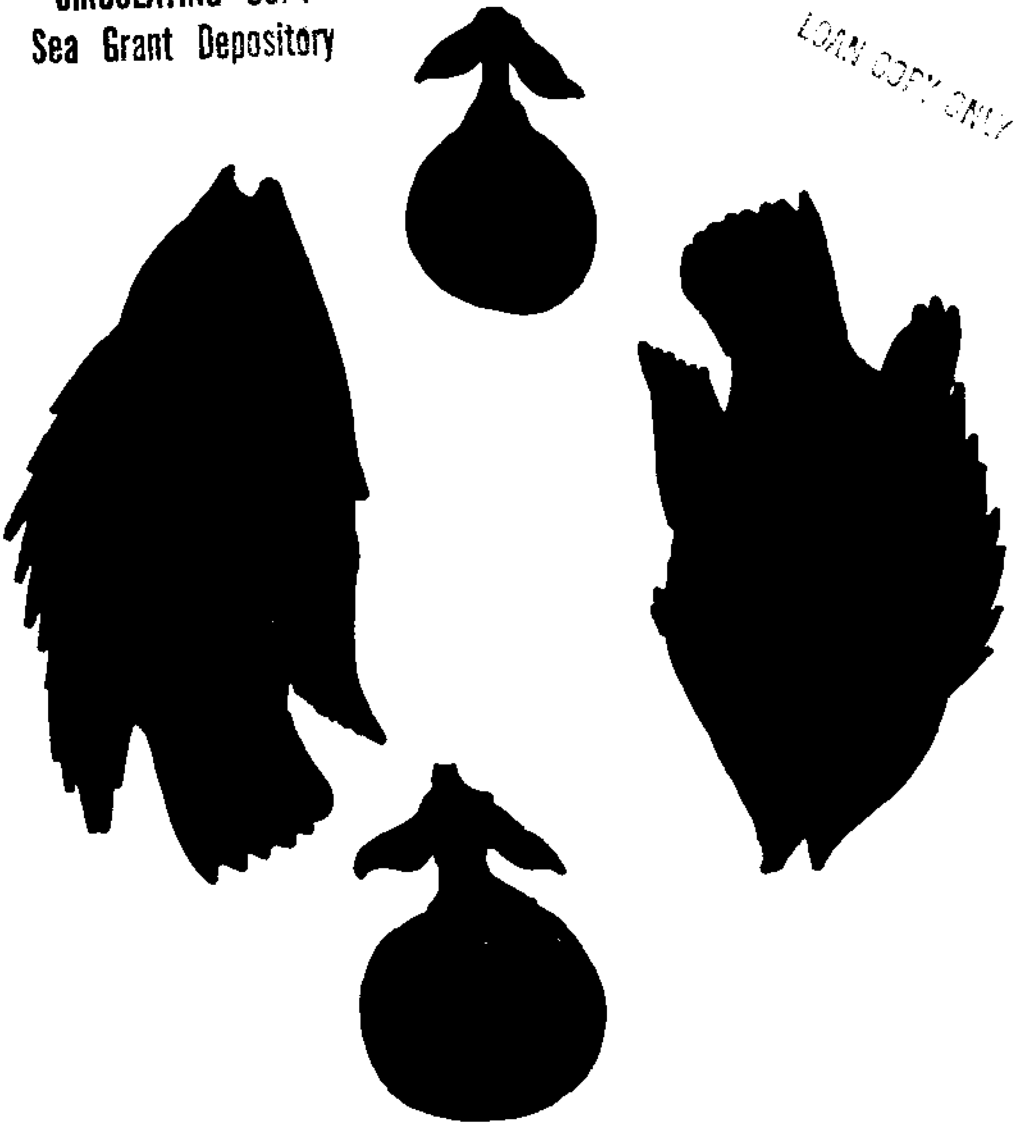
Integrated Aquaculture Project



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ABSTRACT

An experimental integrated aquaculture project co-culturing the fish *Tilapia aureus* and tomato plants was established at the University of New Hampshire's fish hatchery. An indeterminate growth variety of tomatoes was hydroponically grown on floats in two large 423 gallon tanks containing *Tilapia aureus*. Both tanks had approximately 20 plants and began each month with an adjusted fish biomass of five kilograms. The tanks differed by the activation of a gravel trough in tank B through which tank water was pumped and tomato plants grew in the substrate. Water chemistry, fish growth and plant growth were measured. The nitrogen dynamics of both tanks were similar following a pattern expected in biological filtration; however, the ammonia levels of the tank with the gravel trough were twice as low indicating that the microbial population in the trough was better established than in the biofilm of tank A. As a result of the lower levels of ammonia, there was a much higher survival rate present in tank B (with the trough) as compared to tank A. Fish growth was higher in March tank during the starting month of February probably as a result of more stabilized water chemistry conditions. Although stress was a suspect in inhibiting *Tilapia* growth in tank A, the condition factors for the fish in both tanks were not significantly different. Substantial plant growth was noted in both tanks. There were no significant differences of plant growth between the two tanks. The buds and flowers that were observed on the tomato plants during the course of the study failed to fully develop indicating a possible deficiency of magnesium and/or manganese.

INTRODUCTION

The concept of integrated aquaculture combines the raising of marketable fish with hydroponics and the practice of growing crop plants in a nutrient-rich water medium. The fish excrete ammonia as a waste product that can become toxic to them at high levels (Moe 1982). *Nitrobacter* and *Nitrosomonas* bacteria can grow on the surface of plant roots and convert ammonia to nitrite and nitrate, respectively (Schlesinger 1981). The conversion, called nitrification, provides nitrogen in a usable form for the plants and removes toxic ammonia from the water. In addition, the roots collect detritus from the water. The end result is a biological filter, enabling the water to sustain a fish population in a type of symbiotic or mutualistic relationship. Theoretically, all that needs to be added to the system is the fish food; no fertilizer, pesticides or ammonia-removing compounds should be necessary.

The concepts of integrated aquaculture has been initially researched at the New Alchemy Institute in East Falmouth, Massachusetts (Baum 1983) which led to the establishment of an experimental facility at the Massachusetts Southeast Regional Correctional Center in Bridgewater, MA (Levi 1991). Baum (1983) describes the New Alchemy system in which Blue Tilapia (*Tilapia aureus*) was integrated with the farming of various plant crop species. Hydroponics was used alone and in addition to biofilters in conjunction with indoor solar tanks during the winter months. The 646 gallon transparent fiberglass tanks collected and stored about 6300 kcal/day of heat that was released into the greenhouse structure at night (Zweig 1986).

Two previous experiments that utilized a biofilter/sediment-removal chamber and a plant trough in circuit with either one or a few tanks forming a self-contained recirculating unit preceded the integrated facility in Bridgewater, MA. The first study used a clam-shell substrate as the biofilter bed and celery as the crop plant. Fiberglass panels comprised the biofilter bed in the second experiment. Tomatoes, a European variety of lettuce, cucumbers and a sweet basil were farmed in both experiments. There was considerable success with crop cultivation but the fish growth was much lower than expected, possibly due to the release of hydrogen sulfide during the anaerobic breakdown of detritus caught among the plant roots (Baum 1983).

The New Alchemists attempted to solve the problems by modifying the system, removing the biofiltration/sediment tank, increasing the flow rate through the trough, decreasing the number of fish tanks to two in series, while maintaining the same number of plants and raising the fish water intake tube flowing into the hydroponics trough. Tomatoes and cucumbers were used because of their high biomass yield, commercial value and compatability with greenhouse growing conditions (Baum 1983).

Adjacent to and independent of this third experimental system was one fish tank in circuit with a biofilter tank and no hydroponic trough. The third study was to determine the effects of the biofilter alone. The same amount of fish and fish food was used. As a control, another system comprised of only a fish tank received 1500 grams of sodium chloride as an inhibitor of nitrite toxicity. Such salts are commonly used in indoor single-pond culture (Baum 1983). The plants became deficient in iron, magnesium and potassium. Dilute foliar sprays were used to combat this nutrient deficiency, but they were ineffective. Iron oxide, which was added to the trough in the form of rusty water, also proved ineffective. In spite of these deficiencies a high crop yield was obtained in the hydroponically filtered system -about 6.8 kg of tomatoes and 28.6 kg of cucumbers per plant. Fish growth was similar in all of the tank combinations with the control showing the highest growth. Higher ammonia levels were found in the control and hydroponics tanks than in the biofiltered tank where production and oxidation of toxic ammonia into nitite were in equilibrium. A slight gain in nitrate and a loss of dissolved oxygen and phosphorous was observed. In the hydroponics trough, higher ammonia and nitrite levels occurred in the effluent than the influent, but lower levels of phosphate, dissolved oxygen and nitrate were detected (Baum 1982).

The Bridgewater system was different from the original New Alchemy experiments. In the Bridgewater system, the crop plant, lettuce, was grown directly on top of the tank rather than in a trough set off to the side. A wheel with eighteen wire spokes capable of holding styrofoam floats rested on the water surface. Seedlings were transferred into the 675 gallon tanks where the styrofoam floats were placed between the two wires of each spoke. The combined result of 19 units at the facility yields a weekly harvest of 300 heads of lettuce and a seasonal crop of up to 100 pounds of fresh fish (Levi 1991). Originally bullhead catfish (Levi 1991) were used but the facility has since experimented with striped bass, channel catfish. *Tilapia,* koi, guppies and baitfish (pers comm. Zweig 1992). A plastic mesh root cage was placed 20 cm below the water to prevent consumption of the plants by the fish, while ladybugs were added as a biological pest control. The system won two awards at the 1990 New England Flower Show.

Ron Zweig, president of EcoLogic in Falmouth, MA, used the Bridgewater facility to determine a nitrogen macronutrient budget of an integrated system growing Blue Tilapia and Buttercrunch Lettuce. When the bacterial communities in the tank became established within the first month, almost all of the ammonia and nitrite was converted to nitrate which peaked in the fourth week. After this time, the plants were large enough to remove almost all of the dissolved nitrate. Zweig also used nylon stocking filters in conjunction with an airlift pump to remove detritus (Zweig 1986). In order to combat the deficiencies of iron and magnesium that were again encountered, Zweig added dolomite limestone and steel wool to add magnesium and iron, respectively. To maintain high alkalinity for good decomposition and nitrification, he added garden-variety limestone weekly (Zweig 1986). Unfortunately, he did not mention if these treatments were effective.

Many potential uses for uses for integrated aquaculture have been mentioned in the literature. Fingerlings may be hatched and grown indoors during the winter and transferred to outdoor ponds in the spring, ultimately being harvested in the fall. Also, freshwater clams may be introduced into the rootcage to be harvested for food and/or pearl production. Effluent from fish hatcheries may be run through a hydroponics system for nutrient recycling. Small scale systems may be installed in restaurants to ensure fresh, organically grown produce (Levi 1991). Zweig (1986) suggested that the farming of ornamental plants might improve the economic yield of an integrated system by up to five to ten times that achieved by lettuce production. Integrated aquaculture is being used miles under the earth in caves of western Pennsylvania where the system is sheltered from air pollution and the vegetables are sold to grocery stores and marketed as totally natural and chemical free (pers comm. 1992).

Integrated aquaculture provides an economically sound, environmentally safe, sustainable farming method that is still in its infancy. The objectives of this study were to establish an integrated aquaculture system using *Tilapia* and tomato plants as well as to monitor water chemistry to ensure optimum conditions for fish and plant growth.

MATERIAL & METHODS

SYSTEM DESIGN

The system design consisted of two 635 gallon (2236 L) round tanks that were six feet (178.56 cm) in diameter and three feet (84.32 cm) deep. The tanks were housed in the Anadromous Fish & Aquatic Invertebrate Research (AFAIR) Laboratory at the

University of New Hampshire. These tanks were filled with well water to a depth of 24 inches (59.25 cm) with a total volume of 423 gallons (1489 L). The tanks were labeled tanks A and B. Aeration of each tank was supplied by two six inch (14.88 cm) airstones placed at opposite sides of the tank.

Root cages were constructed from fine mesh window screening by sewing two lengths of the screening together using fishing line and cutting this length to the shape of tanks (figure 1a). The root cages were then placed within the tanks at a four inch depth from the surface (figure 1b). The cages were then supported by four 20 inch (49.6 cm) PVC tubes per tank placed upright upon tank bottoms. Fishing line was also tied to the edges of the root cages and attached to small hooks alongside the outside rim of the tanks to better suspend the root cage (figure 1a). Even with this extra support, the root cages still sagged in certain places to a depth lower than the desired four inches from the water surface due to improper fitting of the cages to the tanks.

A trough was developed using flexible, plastic rain gutter. Two 10 foot (297.6 cm) lengths were used in the construction of each trough. The lengths were cut into two 64 inch (158.72 cm) and two 34 inch (84.32 cm) lengths for each tank. A rectangular trough was constructed from these lengths using rain gutter corner-pieces as connectors. The beginning segment was elevated and the end segment was left hanging in the water to minimize disturbance of the water surface when water flowed through the trough (figure 2a). The trough segments were siliconed together to prevent leakage. The trough systems were suspended approximately two inches (4.96 cm) above the water surface, using twine running up to the building's rafters.

The trough in tank B was then filled with 40 pounds (18.14 kg) of aquarium gravel while tank A's trough was left empty. A submersible water pump was placed on the bottom of tank B and water was pumped from the tank into the gravel trough system. The water flowed passively through the trough and back into the tank (figure 2b). In order to enhance water flow, the trough was adjusted to create a negative slope of 0.06°.

The trough in tank B became the active trough system, while that in tank A remained unused and remained positioned ready to be activated if it was deemed absolutely necessary for the survival of the system.

Two fluorescent light fixtures, each containing a mixture of cold and warm bulbs, were suspended from the rafters above each tank. The lights were set on a 16:8 light:dark cycle. Upon addition of the plants, the fixtures were adjusted to a height within eighteen inches (43.2 cm) above the tallest plant and were occasionally adjusted as the plants grew in height.

WATER CHEMISTRY

The water chemistry of the system was tested twice each week in the early stages of the project; however, once no large scale changes were observed in that time-frame and the costs of reagents were considered, the testing was done on a weekly basis. Water samples were collected from four distinct sites in each tank (figure 4a) using a common turkey baster. Initially, samples were also taken from two depths - one within the root cage and the second from within the fish zone (figure 4b). After several weeks with no distinct differences between the zones and considering the costs of reagents, this was discontinued and the remaining samples were collected from within the root cage.

The water was tested for ammonia, nitrite, nitrate, phosphate and hardness using LaMotte test kits. With the exception of the hardness test that used a titration method, all of the tests were colorimetric. Nitrite interference with the nitrate readings was corrected using the formula obtained by a LaMotte technician: $[NO_3\text{-}N] - ([NO_2\text{-}N] \times 5.5)$. Oxygen and temperature readings were also taken at these sites using an Orion oxygen meter.

TILAPIA

The tropical freshwater fish *Tilapia aureus* was used in this system. Thirty three pounds (14.97 kg) of fish were obtained from AquaFuture, Inc. in Turners Fall, Massachusetts, as well as 100 pounds (45.36 kg) of *Tilapia* feed. Five kilograms of *Tilapia* were added to both tanks. The extra fish were held in a holding tank to serve as a reserve. The fish were initially fed 6% of their body weight but due to water fouling, it was reduced to 1% and then finally raised to 2% per day. In order to minimize water fouling, the feeding was split into 1% in the morning and 1% in the evening. The tank bottoms were also siphoned daily in order to remove excess waste and food material.

Monthly measurements of *Tilapia* were obtained on 13 February, 6 March, & 4 April 93. Measurements included length, weight and girth for a subset of 24 individual fish and total weights and numbers were determined for the fish population in each tank. Upon determination of the total tank biomass, each tank population was then readjusted to five kilograms with extra fish being placed in the holding tanks.

TOMATO PLANTS

The plants used in the system were an indeterminate (vining) form of tomato species donated by the University of New Hampshire Greenhouses. First, the plants were removed from their peat/soil flats. The soil was then gently rinsed from the plants' roots with cold water since it had an anaesthetizing effect on the plant minimizing shock (Nicholls 1990). They were then transplanted into thick closed cell styrofoam floats measuring six by six inches (14.88 cm) and two inches (4.96 cm) thick. An individual plant was placed within a small groove in half of the float and held in place using a piece of duct tape. The second half of the float with its corresponding groove was placed over this and the two halves of the float were secured by duct tape along the edges (figure 3). The result was a float with a small circle in the center in which the plant rested with the stem and leaves protruding on top and the roots emerging through the bottom.

Each float was numbered and holes were punched through a corner of each float enabling lengths of twine to be tied between the floats and the rafters of the building. The plants in their floats were then randomly placed within the system where space would permit. There were 20 plants placed in each tank. The lengths of twine attached to each float were wound slightly up the plants so they could act as supports as the plants grew up the twine.

After the first measurements of plant growth were taken, the support system was modified. That is, the single lengths of twine running from float to rafter were cut into two segments, one with a safety pin attached to its end and the other with its end taped. The new arrangement allowed for the simple attachment and removal of the plant from the support system, making measurements easier.

Four plants without floats were also placed within the gravel trough, two spaced along each of the long trough segments. The suspension lines for the trough acted as support lines for the plants.

All of the plants were measured monthly. Total lengths (from the beginning or base of the stem to the tip of the plant), surveys of the numbers of buds and flowers and general observations were taken for each plant.

After approximately eight weeks from the time that the project became operational, the final observations and data were collected on 4 April 93. The fish and plants were terminated and the data analyzed.

RESULTS

WATER CHEMISTRY

The nitrogen dynamics in both tank A and B followed the same basic pattern of successive peaks of ammonia followed by nitrite and then nitrate (figure 5). The nitrite and nitrate peaks were higher in tank B (figure 5b) than in tank A (figure 5a). The reverse was true for ammonia levels (figure 6) with the ammonia levels peaking at 8 ppm in tank A while only reaching 4.5 ppm in tank B. Also, the ammonia concentrations in tank A took one week longer than tank B to drop to zero. Both tanks had a slight increase in ammonia levels in the last two weeks of the study just after the fish invaded the root cage. The same nitrogen dynamics in the gravel trough of tank B followed the same pattern as the tank water with values identical or slightly lower.

Phosphate levels quickly increased from zero to 0.8 ppm within the first three days of the study in both tanks (figure 7). No major differences were observed between the two tanks. Throughout the duration of the project, the phosphate concentrations continued to increase.

The water hardness in both tanks generally increased as the study proceeded. The levels of calcium carbonate in tank B were significantly higher and increased at a faster rate than in tank A (figure 8). The final hardness levels on 4 April were approximately 30% higher in tank B than tank A. The trough calcium carbonate levels were not significantly different from that within tank B.

Oxygen levels were very high (figure 9) and the overall temporal trends of increases and decreases mirrored temperature (figure 10). The one anomaly in the oxygen data on 16 February in tank B may be considered a sampling error or the only true reading depending on whether the Orion meter was functioning correctly. Due to the correlation between the dissolved oxygen and water temperature readings (figures 9 & 10), the water in both tanks appears to be saturated with dissolved oxygen.

TILAPIA

Figure 11 shows that the *Tilapia* in tank B had a much higher overall survival (98%) than those in tank A (72%). The *Tilapia* mortalities basically occurred in a one week period (figure 12). Only one fish died in tank B, while 12 *Tilapia* in tank A died during this period.

The overall change in *Tilapia* biomass each month from the adjusted five kilograms was much higher in tank B compared to tank A (figure 13). Tank A showed a decrease in biomass during February as evident by the 6 March sampling and only a slight increase during March. The mean biomass of individuals in tank B followed the similar trend, being larger in tank B versus tank A (figure 14). There was a greater increase in individual biomass during March than February.

Condition factors are calculations based on the weight and length of a fish and are often used to judge overall fish health. The condition factors of the *Tilapia* based on length and weight relations of individuals were not significantly different between the tanks nor over the course of the project (figure 15).

TOMATO PLANTS

Almost all of the plants in both tanks A and B showed significant height increases over the course of the project (figure 16).

In tank A, plant #9 which had measured 21 cm upon introduction was broken while attempting to clean the root cage and was removed. Because it was not available for subsequent data collection, the measurement from 13 February 93 was disregarded. Also, plants #1 in both tanks were removed and not used in the main integration study. Some plants showed a complete lack of (or even decrease in) growth between 6 March and 4 April due to cleaning accidents.

There were no significant differences in mean growth of the tomato plants between tanks A and B (figure 17). A general increase in plant height over time is clearly demonstrated.

In addition to the height data, the number of buds or flowers were recorded (figure 18). Because the plants were germinated in December and the experiment ran approximately two months, there was not enough time for fruit to appear. The mean number of buds in tank A decreased over time, although the standard error was very large and this may not be significant. The mean number of buds in tank B was erratic and the standard error was very large.

MICROBIAL COMMUNITY

Light microscopy observations of the well water showed that no visible microorganisms present. Very little if any microbe activity was seen in the water of tank A and tank B; however, a variety of microorganisms comprised a thriving population in both the biofilm of tank A and in the gravel trough of tank B (figures 19a-e). A variety of ciliates, rotifers, nematodes, a shelled amoeba and an oligochaete worm were observed.

DISCUSSION

The *Tilapia* in this integrated system grew significantly during the two month study period (figure 13) especially in tank b which had the activated trough. The tomato plants, while not exhibiting any potential fruit development, produced much biomass and grew significantly also (figure 17). The water chemistry of the system began to stabilize and exhibit a predicted pattern especially in regard to the nitrogen dynamics (figure 5) that were critical for the survival of both the *Tilapia* and the tomato plants.

The *Tilapia* in tank B increased a greater amount than in tank A in overall biomass from the adjusted 5.0 kg of each sampling period (figure 13). Although the first negative reading in tank A biomass was attributed to fish mortality, the *Tilapia* in this tank still exhibited very little increase in biomass. One difference between the two tanks was the large amount of organic matter present in tank A fouling the root cage, tank sides and the foam layer on the water surface. Thus, the increased organic matter may be acting as a stressor on the fish. Other factors that may also have acted as stressors inhibiting the growth in tank A may include pH and H_2S, neither of which were measured. The increased organic matter covering the roots of the plants could have created anaerobic zones promoting the release of hydrogen sulfide (Baum 1983) as well as promoting denitrification of nitrate back to ammonia (Schlesinger 1981) which may be a possible answer to the slight ammonia elevation during the final weeks of the study. In addition, there was more growth during March than February, which may be attributed to the ammonia stress during late February and the dynamic fluctuations in the water chemistry, particularly nitrogen related.

The mean individual weight of the *Tilapia* followed the identical pattern as the overall fish biomass (figure 14). If the biomass of the fish in the tank was increasing then the average fish would also be getting larger. As in overall biomass, a greater increase in biomass per sampling period was observed over time in both tanks and the fish in tank B had a substantially greater increase than in tank A.

Although stress is the major suspect for limiting the *Tilapia* growth during the early stages of the project and especially in tank A, the condition factors calculated for the *Tilapia* suggest otherwise. Condition factors expressed as weight/length^3 are often used in growth and stress investigations. A decline in the condition factor is usually observed in fish experiencing stressful situations such as high density, acidification and adverse environmental conditions. The decline is usually interpreted as a depletion of energy reserves, caused by changes in feeding behavior or metabolic rate due to stress (Goede & Barton 1990). There was no change in the condition factors of the fish over the three sampling dates and no difference between tanks (figure 15). If the condition factors are used as a measure of stress, this would suggest that some other factor or factors besides stress are involved in inhibiting the growth of the *Tilapia* in the early stages of the project and in tank A.

Although the condition factors suggest that stress did not play a role in inhibiting *Tilapia* growth, the ammonia peaks can be correlated with the *Tilapia* mortalities that occurred during late February and early March. Ammonia is the most toxic form of nitrogen to fish (Moe 1982). A concentration of 2.4 ppm of ammonia over a 48 hour period can result in a 50% mortality of *Tilapia aureus* (Stickney 1993). The pH of the water can also play an important role in determining the toxicity of compounds such as ammonia (Moe 1982); this may explain why *Tilapia* were able to withstand higher ammonia levels with lower mortalities than expected. Unfortunately, we were unable to obtain any pH readings. The peaks of ammonia (figure 6) occurred in both tanks just prior to the fish deaths (figure 12). The highest *Tilapia* mortalities occurred in tank A (figure 11) which had the highest ammonia levels. Since the only difference between the design of the two tanks was the presence or absence of the gravel trough, the presence of the trough appears to play a vital role in stabilizing the nitrogen dynamics of the system, promoting a healthy environment for the fish.

The nitrogen dynamics in both tanks of the integrated system (figure 5) followed an identical pattern of nitrification observed in a biological filter (figure 20). Biological filtration involves the transformation of toxic waste substances such as ammonia into relatively nontoxic nutrients through the activity of organisms, primarily bacteria (Moe 1982). Nitrification is a process that converts ammonia into the more oxidized state of nitrate, often involving nitrite as an intermediate. Two separate bacterial communities are involved in the nitrification process. The bacterial genera *Nitrobacter* is responsible for the transformation of ammonia into nitrite while *Nitrosomas* converts nitrite into nitrate, the least toxic form of the nitrogen species (Schlesinger 1991).

The *Nitrobacter* community quickly became established in both tanks early in the study due to the presence of fish waste in the form of ammonia. As nitrite levels increased, *Nitrosomonas* became established that could use nitrite as an energy source converting the nitrite into nitrate. This community succession is responsible for the characteristic pattern of nitrification (figure 20) that was observed in both tank A and B (figure 5). Once the communities of *Nitrobacter* and *Nitrosomonas* are established, oxidation of ammonia and nitrite occurs almost as quickly as they are formed. As a result, these compounds never accumulate in the system and only nitrate builds to high levels. The nitrate, although relatively non-toxic to fish at low concentration, can become toxic with increasing accumulation (Moe 1982).

In addition to the ammonia required to initiate the nitrification process, a substrate with high surface area is necessary for the bacterial colonization (Moe 1982). In tank A, the bacteria colonized the sides of the tank forming a distinct biofilm. The abundant ciliate, rotifer and nematode populations within the biofilm (figures 19a-e) infer the presence of the much smaller bacterial communities on which they feed. In tank B, there was no biofilm present on the sides of the tank; however, the material in the gravel trough was rich in microorganisms also (figures 18a-e) indicating the presence of the bacteria.

The bacterial communities in the trough of tank B were probably better established and more efficient at denitrifying the ammonia since the ammonia levels in tank A were higher and had a lag time before dropping to zero when compared to tank B (figure 6). The gravel in the trough may have provided more overall surface area for the bacteria than the sides of the tank. Also, nitrification is a very aerobic process (Schlesinger 1981) and the water rippling over the gravel in the trough may have provided enhanced oxygenated zones in the trough promoting the growth of these bacteria.

The tomato plants in the system played the role of removing the accumulating nitrate. It was originally thought that the plants would prove vitally important in the uptake and removal of ammonia; however, the microbial community appeared to be the dominant player in ammonia removal from the system. Their role became evident as the tomato plants exhibited signs of nitrogen deficiencies, such as the yellowing of the lower leaves (Kenyon 1992), despite the very high levels of ammonia in the system at the time. Once the nitrate levels increased and the ammonia levels subsequently disappeared, the leaves regained their characteristic green color, further indicating that the plants can more efficiently take up and utilize nitrate. However, the plants may be involved to some degree in the ammonia removal. After the *Tilapia* breached the root cage in both tanks and consumed a substantial portion of many of the tomato roots, the ammonia levels increased slightly (figure 6). Although the levels of nitrate were much higher in tank B, there was no difference between the amount of growth exhibited by the tomato plants in either of the tanks (figure 17). This suggests that there was abundant nitrogen for the growth of plants in both tanks.

Phosphate concentrations generally increased in both tanks at the same rate and continued to increase over the duration of the project (figure 7). Since the initial well water in the system had 0 ppm phosphate, the phosphate was most likely introduced into the system through the fish food that contained 2.32% phosphorous. This would account for the general increase in concentration as phosphate entered the system. The fact that the phosphate levels did not begin to level off or reach a plateau may suggest that the plants were either deficient in their ability in uptake and utilization of the phosphate or that the microbes and the plants had an overabundance of phosphate available to them and that phosphorous was not limiting to their growth in this situation.

Phosphate is an important factor in plant growth, being needed primarily for the development of flowers and fruit and the growth of roots (Nicholls 1990). Symptoms of phosphate deficiency include dark, dull and discolored leaves, poor root development and very little branching (Nicholls 1990). The tomato plants within the system showed no symptoms of any phosphate deficiencies; however, these plants did show a distinct lack of bud and flower development. Since there is no deficiency of phosphate in the water in the tanks and there were no symptoms of deficiency in the plants, it can be assumed that there is some micronutrient necessary for this function that is below the required level for bud and flower development.

The micronutrient magnesium plays a very important role in the transport of phosphorous within the plant (Nicholls 1990). Although phosphorous was abundant in the system as phosphate, a lack of magnesium would slow this uptake and transport, inhibiting bud growth and development. One of the symptoms of magnesium deficiency is slow or no development of flowers.

Another important micronutrient for flower blooming is manganese. Symptoms of deficiency include poor blooming and dull colors of the flowers (Nicholls 1990), which was seen in those buds that managed to bloom. Although phosphate was abundant in the system, a deficiency of the micronutrients magnesium and manganese could account for the observed lack of bud development (figure 18).

In reviewing the water hardness or buffering capacity of the system, several possibilities arise for the general increase noted in both tanks and the greater increases observed in tank B compared to tank A (figure 8). In testing the initial well water used, a hardness ($CaCO_3$) reading of 82 ppm was observed. The initial increase was believed to be due in part to calcium compounds within the *Tilapia* food that contained 3.53% calcium. These added compounds would account for the similar concentrations observed between the two tanks in the beginning weeks.

As the system became more established, the presence of algal communities may have developed as part of the biofilm along the sides and on the root cage of tank A and in matted communities in the trough of tank B. Photosynthesis and the consequent extraction of carbon dioxide from the water acts to increase the deposition of calcium bicarbonate in the water increasing the water hardness (Hines 1970). As the algal communities developed, photosynthesis may have increased causing an increase in the calcium carbonate concentrations of both tanks A and B. Possibly, there was a greater surface area of the gravel enabling the algal community within the trough to become better established than tank A's biofilm community thus exhibiting a greater calcium carbonate increase.

The composition of the gravel in the trough may also have contributed to the higher hardness readings in tank B. Levels of calcium carbonate may have increased as a result of direct leaching of such compounds from the trough gravel.

In summary, an equilibrium was observed in the system's water chemistry with the classic nitrogen succession and a steady increase of both phosphate and water hardness levels. Substantial growth occurred in the tomato plants; however, due to magnesium and manganese deficiencies, no buds developed or upon forming, they did not flower. As a consequence of this blockage of sustained flowering, no fruit was formed. The fish growth and biomass dropped substantially at first in tank A due to high ammonia levels but then increased slightly upon equilibrium of the water chemistry. Fish growth and biomass increased steadily in tank B and was greater in March than February. Overall fish growth was greater in tank B than A. The trough appeared to be an important factor in the noted growth difference of the two tanks by acting as a filter for particulates and adding calcium carbonate to buffer pH levels. Both conditions may have caused stress and reduced the growth of *Tilapia* in tank A. Also, the trough system played a dramatic role in stabilizing the water chemistry, particularly the nitrogen dynamics, therefore deterring fish mortality. This system, particularly tank B which had the trough, was very successful in producing both substantial fish and plant growth over the relatively short two month period that is was operational. There is, however, some room for modification.

In reviewing the general design of the system, it would probably be more advantageous to chose a plant species that could support itself or to have some other support system than the strings running from the floats to the rafters. Other modifications could include individual root cages for each plant, a white bottom of the tanks allowing for easier location of the fish during sampling, some type of particle filter in conjunction with the trough system, as well as the inclusion of some other companion plant or insect along with the main crop plant to be used as a biological pest deterrent.

How this integrated system would apply or succeed using other plant or fish species could be very interesting. The addition of a bottom feeder such as a catfish or crayfish both which are very marketable could be useful in reducing turbidity and eliminating the need for daily siphoning of bottom debris. Transferring this basic concept to other types of systems such as marine instead of freshwater could also prove valuable. There are many exciting possibilities and applications for such an integrated aquaculture system.

LIST OF FIGURES

FIGURE 19: Photographs of larger members of the microbial community residing in the biofilm of Tank A and the gravel trough of Tank B. Representatives include **(a & b)** ciliates, **(c)** a shelled ameoba, **(d)** rotifers and **(e)** a small oligochaete seen in the gravel trough.

FIGURE 20: The typical patterns of waste nitrogen compounds (ammonia, nitrite, and nitrate) during the first 48 days of a new aquarium using a traditional undergravel filter (reprinted from Moe 1982).

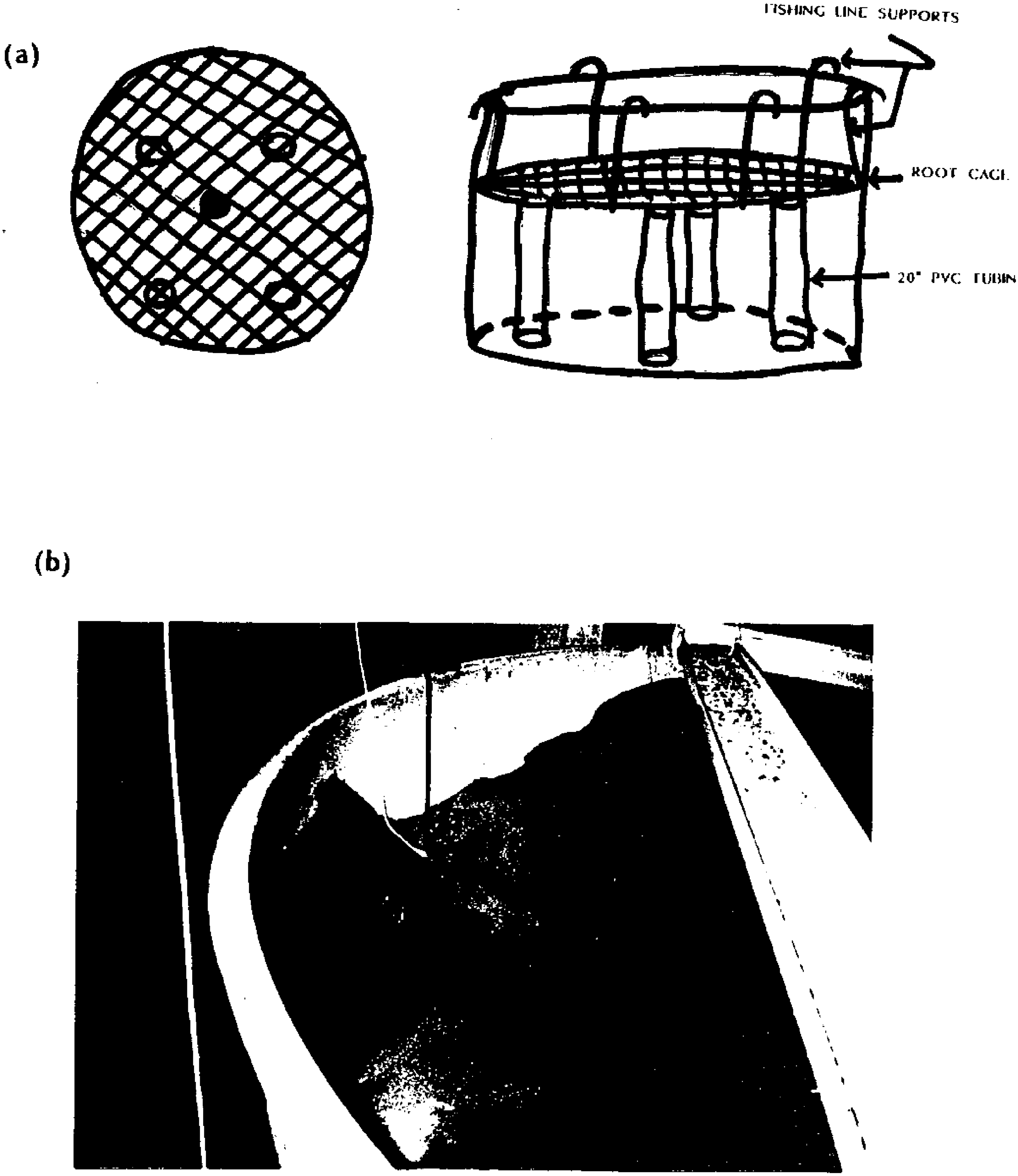

FIGURE 1: (a) Diagram of the mesh root cage - an overhead and side view of placement in the tanks and **(b)** a photograph of the cage during system establishment.

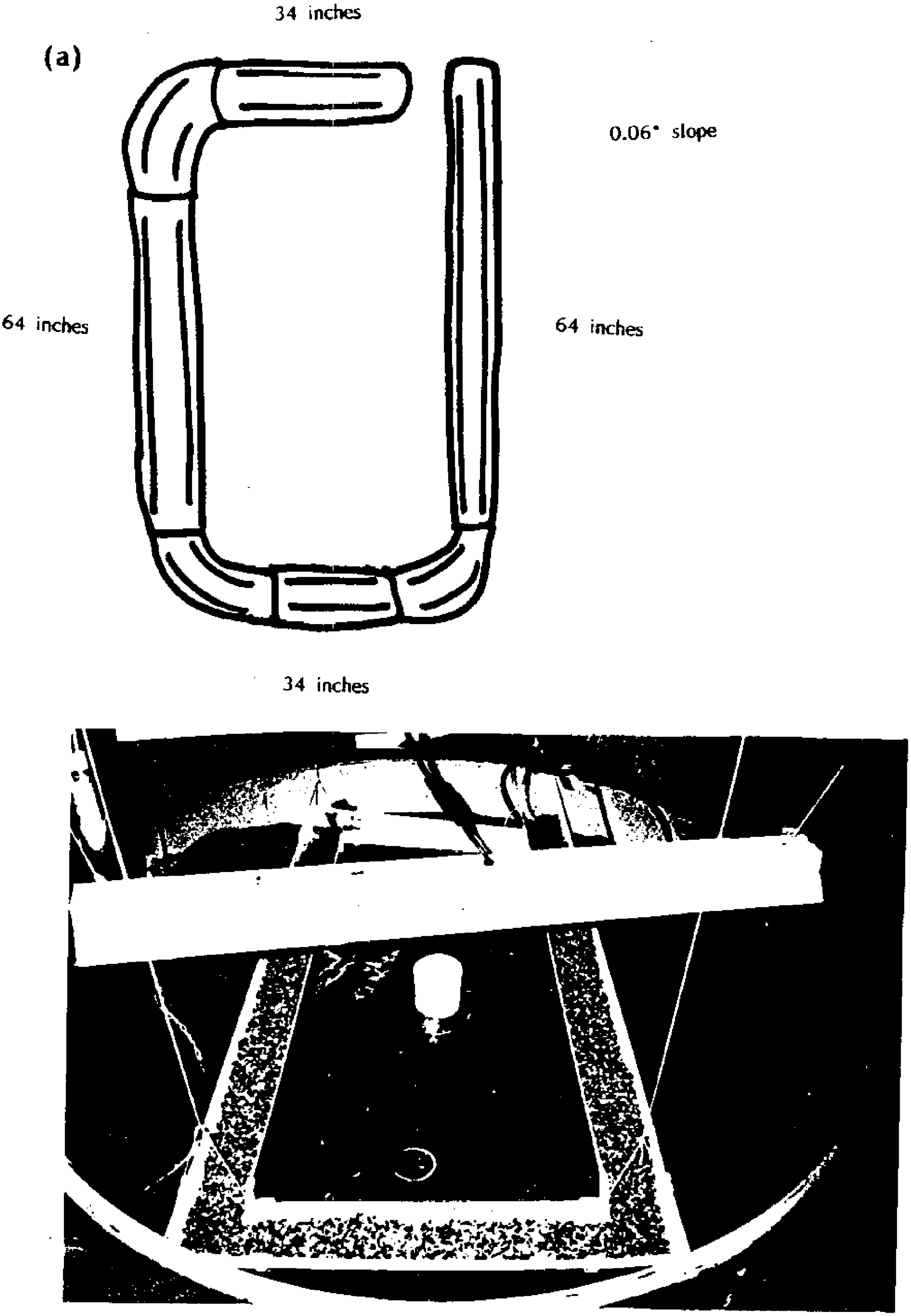

FIGURE 2: (a) An overhead sketch of the trough system and (b) photograph of the activated gravel trough system of Tank B.

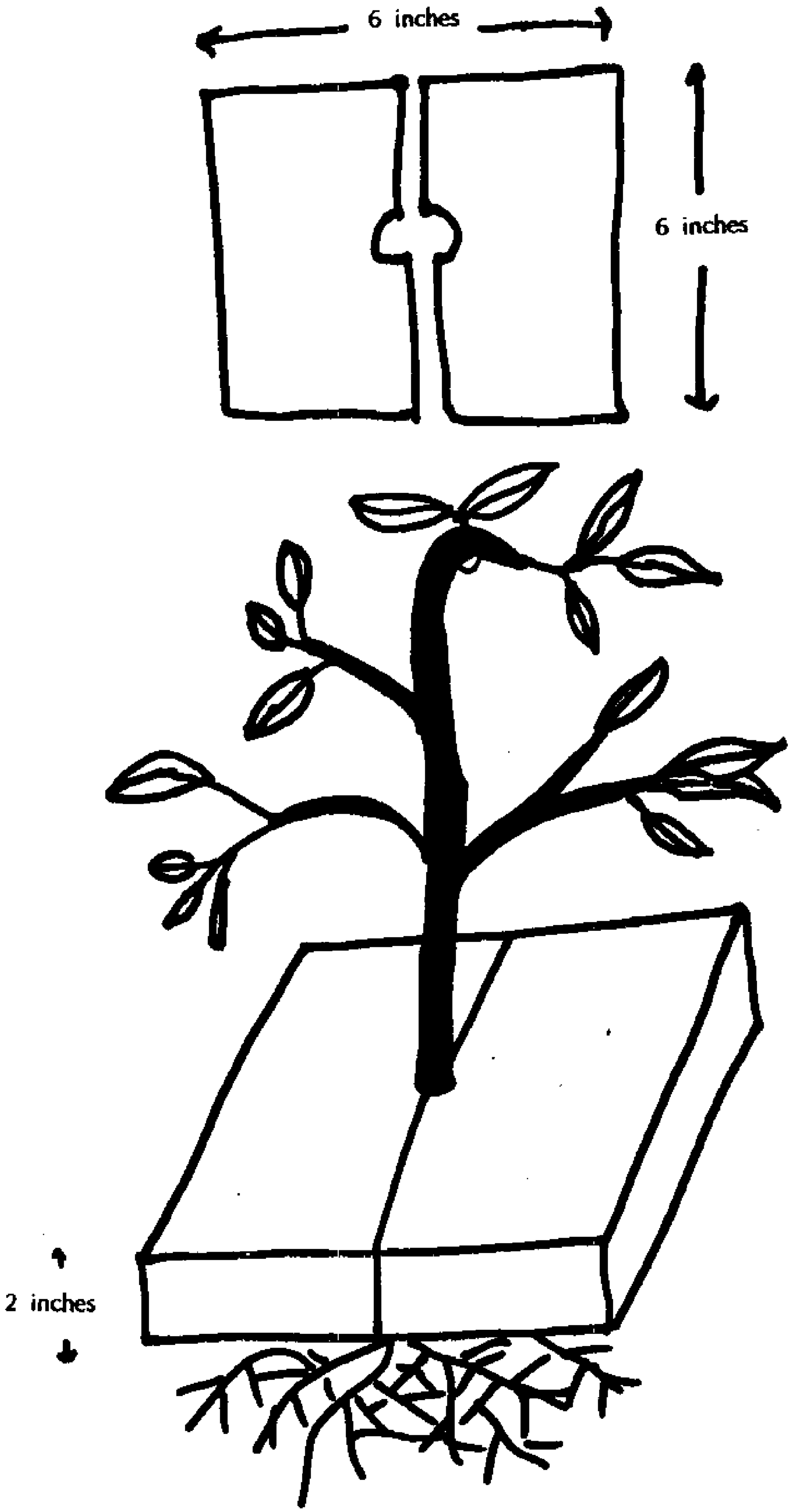

FIGURE 3: Diagram of styrofoam floats used for hydroponic growth of the tomatoes.

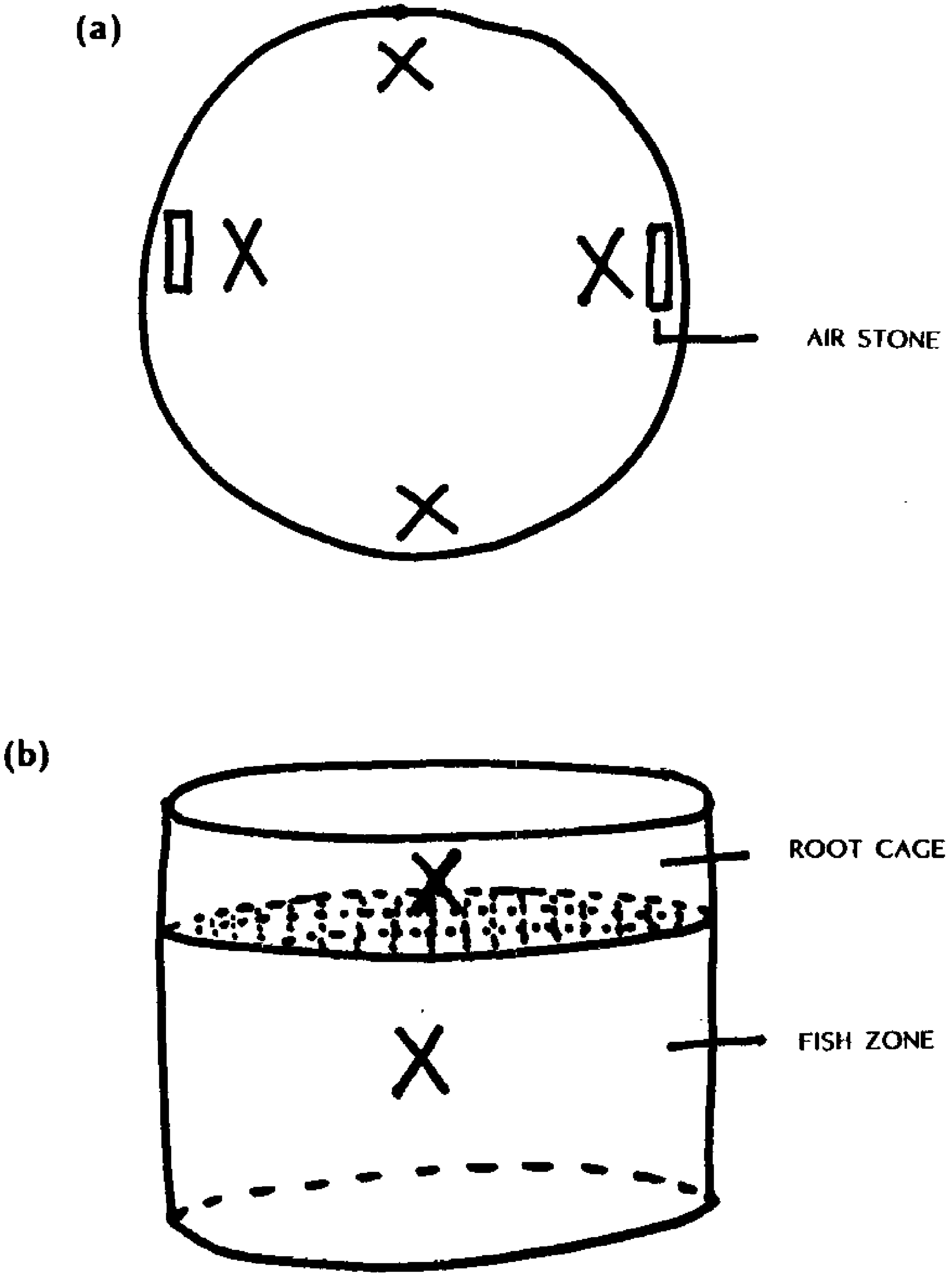

FIGURE 4: (a) An overhead view of the four sampling sites (X) in each tank (air stones are shown as rectangles) and (b) the sampling depths in the root cage and fish zone.

NITROGEN DYNAMICS

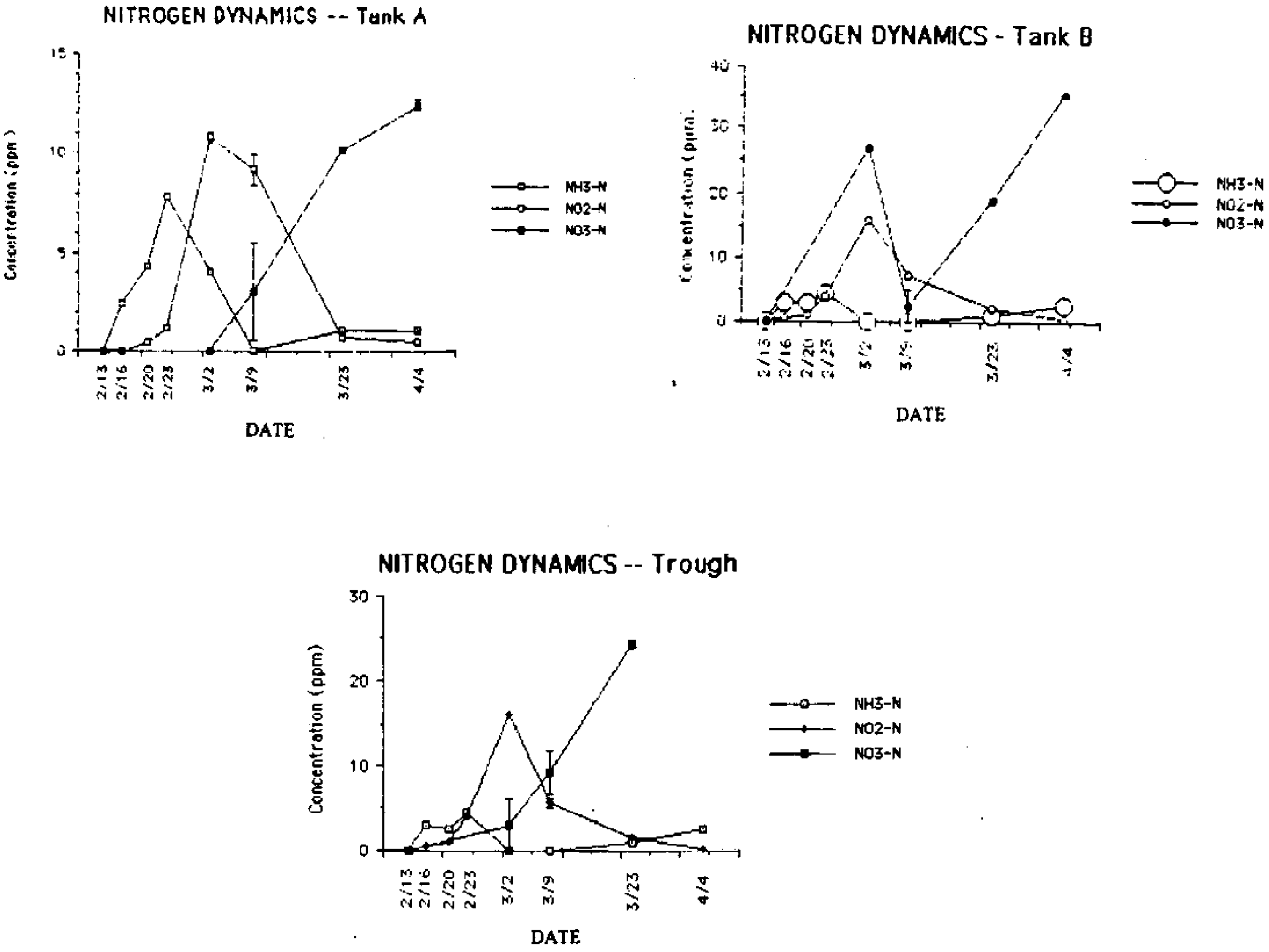

FIGURE 5: The nitrogen dynamics showing the temporal fluctuations of ammonia, nitrite and nitrate in (a) Tank A, (b) Tank B and (c) within the trough system of Tank B. Note the differences in scale.

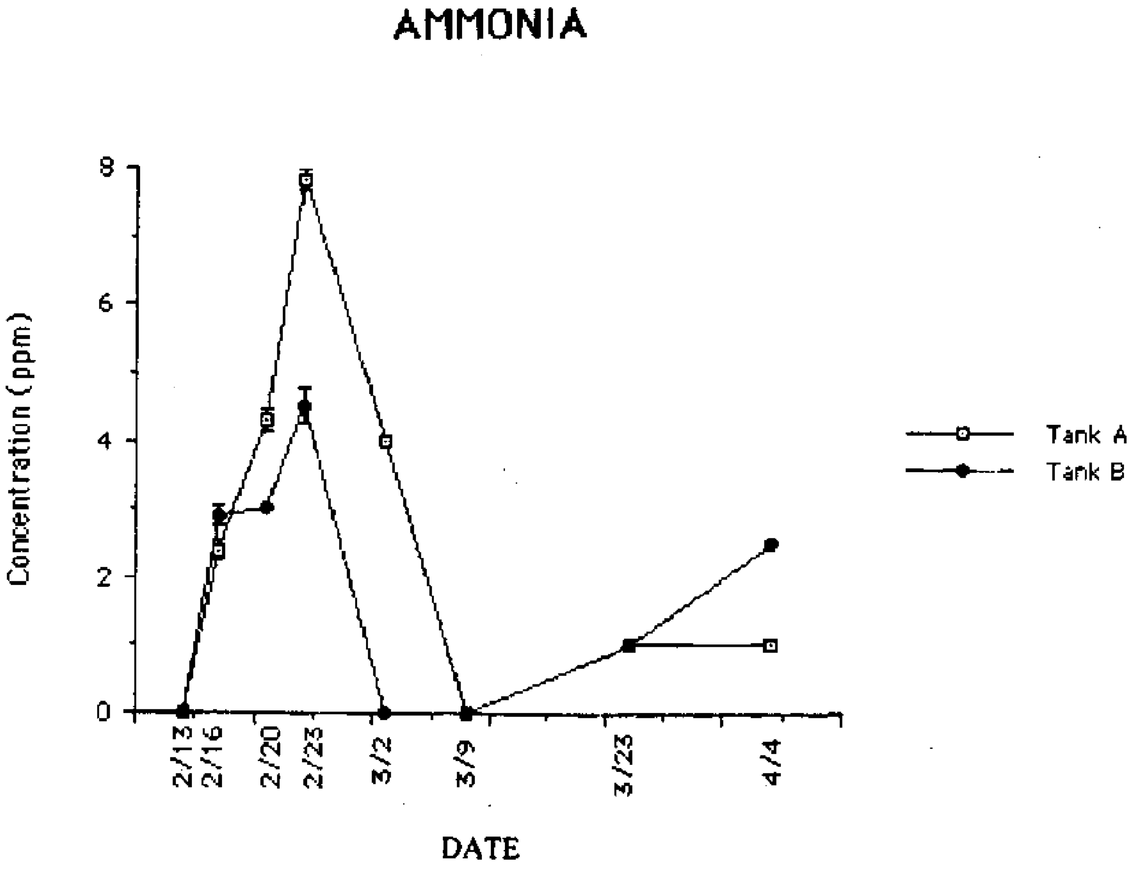

FIGURE 6: Comparison of ammonia levels between Tanks A and B.

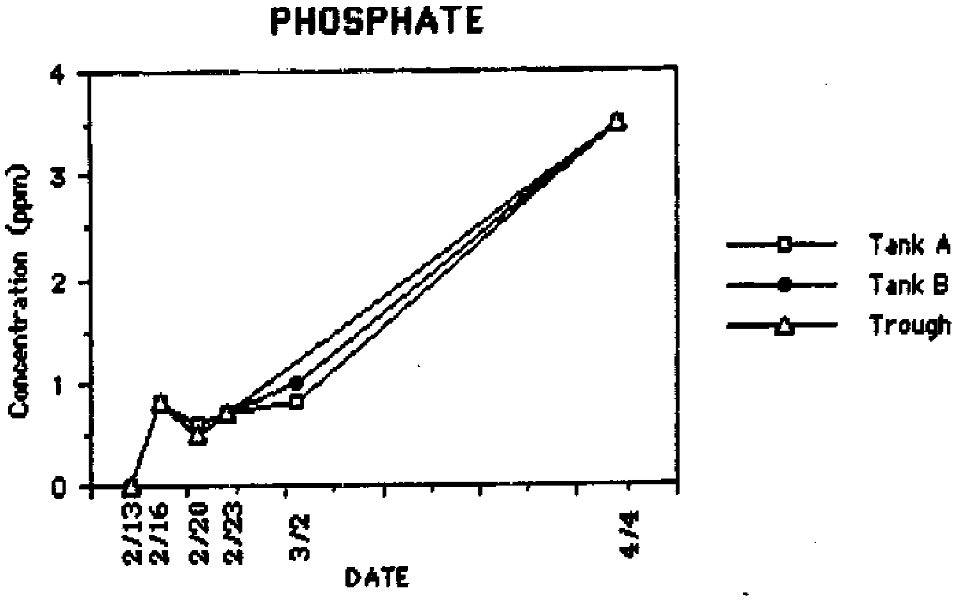

FIGURE 7: Comparison of orthophosphate (PO_4) concentrations in Tanks A and B and the trough of Tank B.

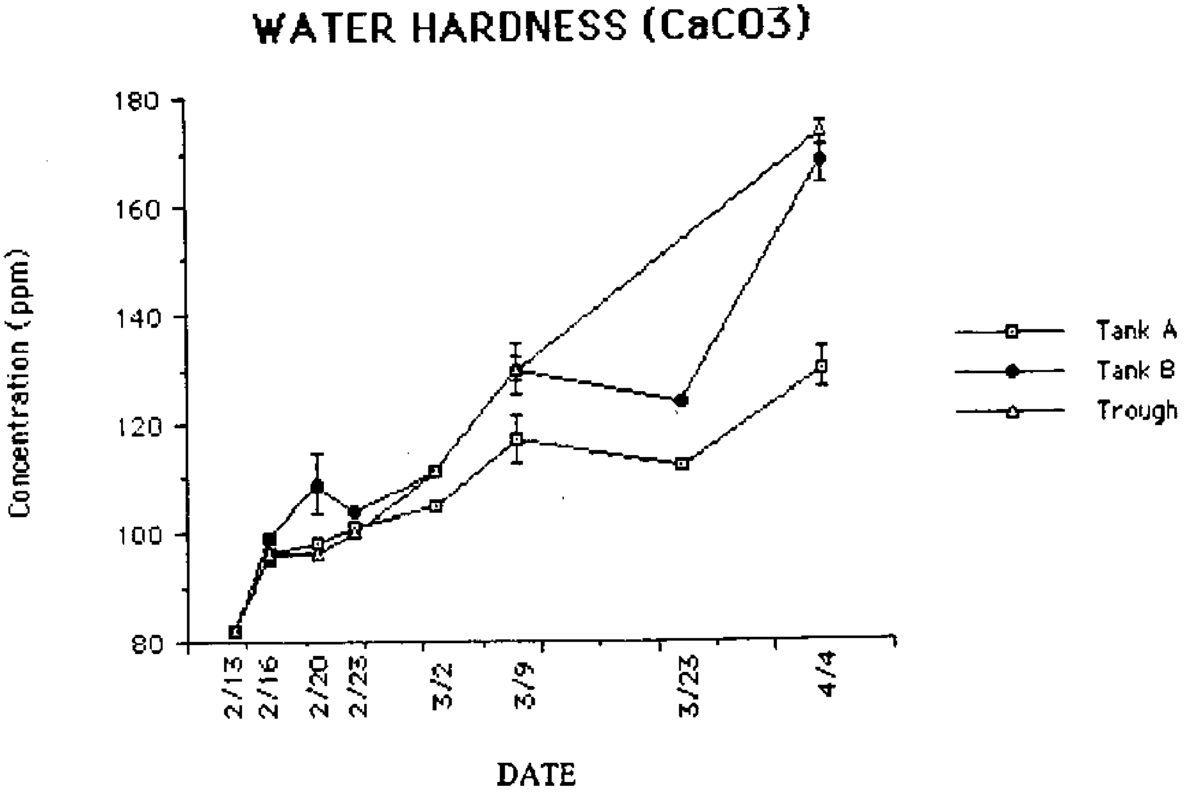

FIGURE 8: Comparison of water hardness measured in ppm calcium carbonate ($CaCO_3$) in Tanks A and B and the trough of Tank B.

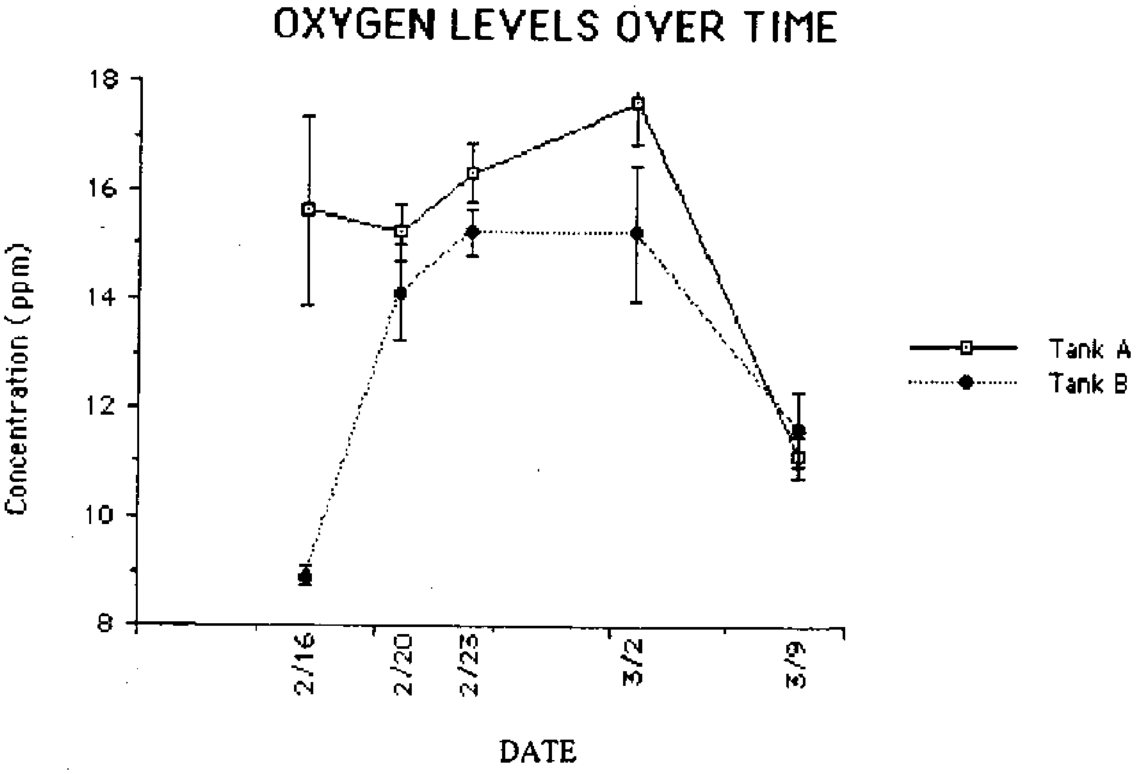

FIGURE 9: Comparison of dissolved oxygen levels between Tanks A and B.

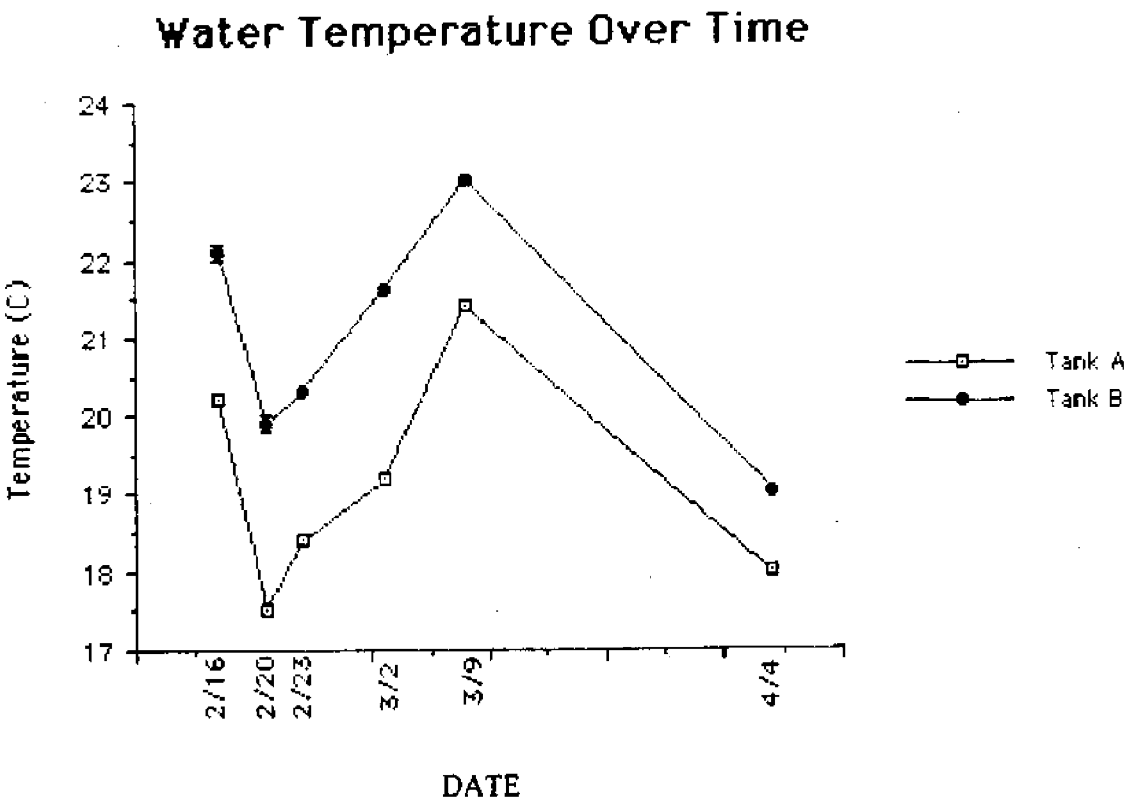

FIGURE 10: Comparison of water temperature between Tanks A and B.

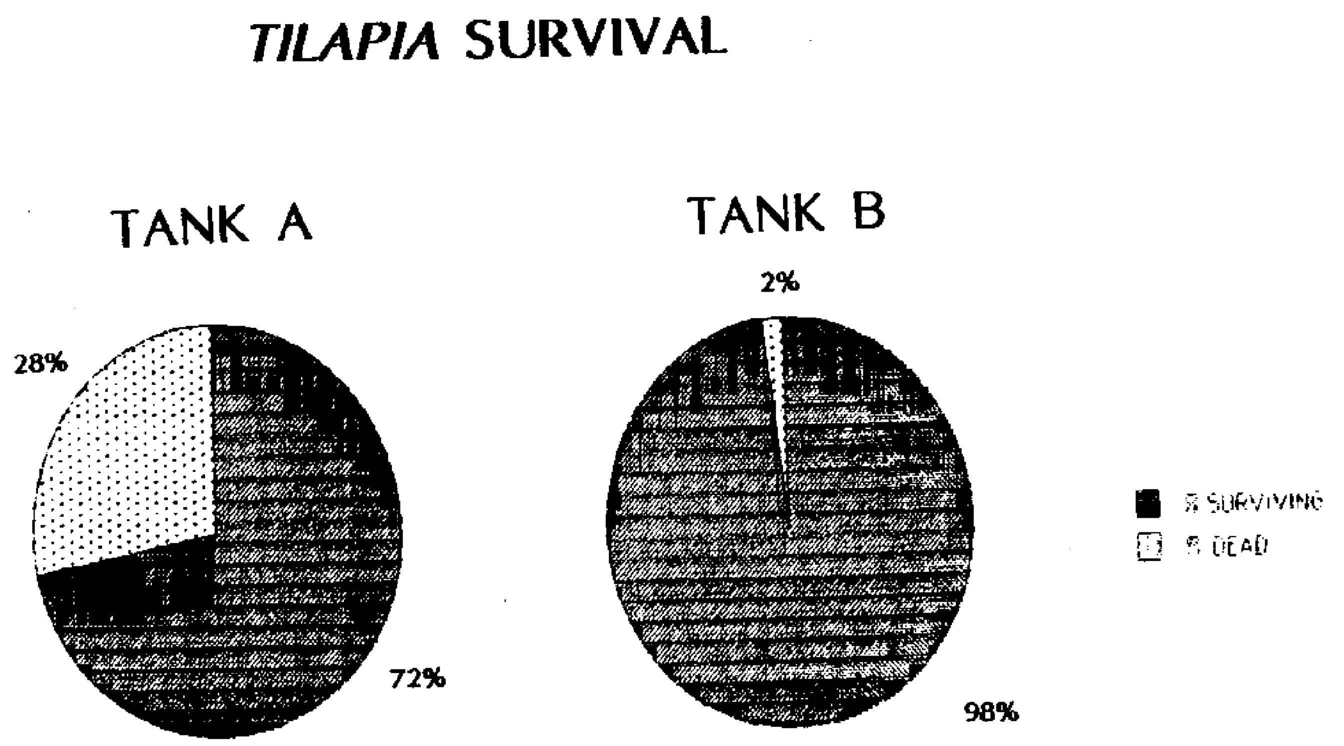

FIGURE 11: The overall survival percentages for the *Tilapia* in Tanks A and B.

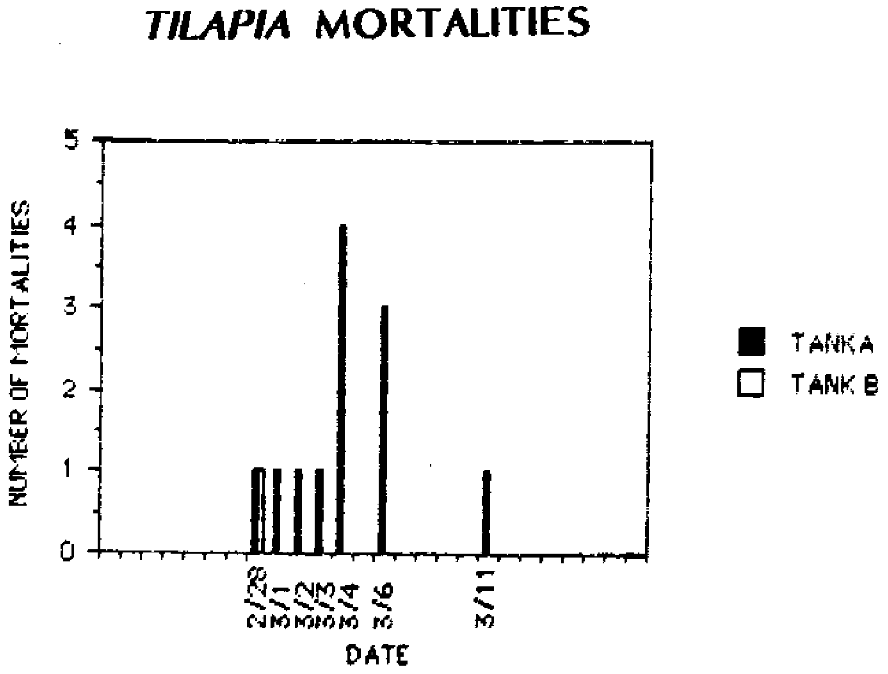

FIGURE 12: *Tilapia* mortalities over the course of the project - a temporal look.

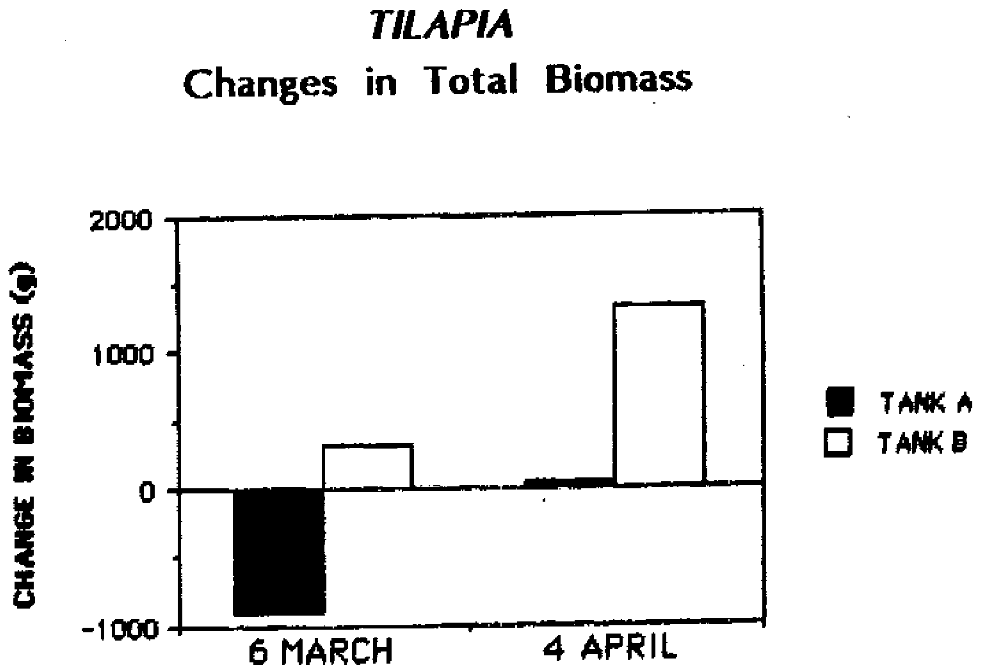

FIGURE 13: Changes in the total *Tilapia* biomass in each tank each month from the adjusted 5 kg biomass.

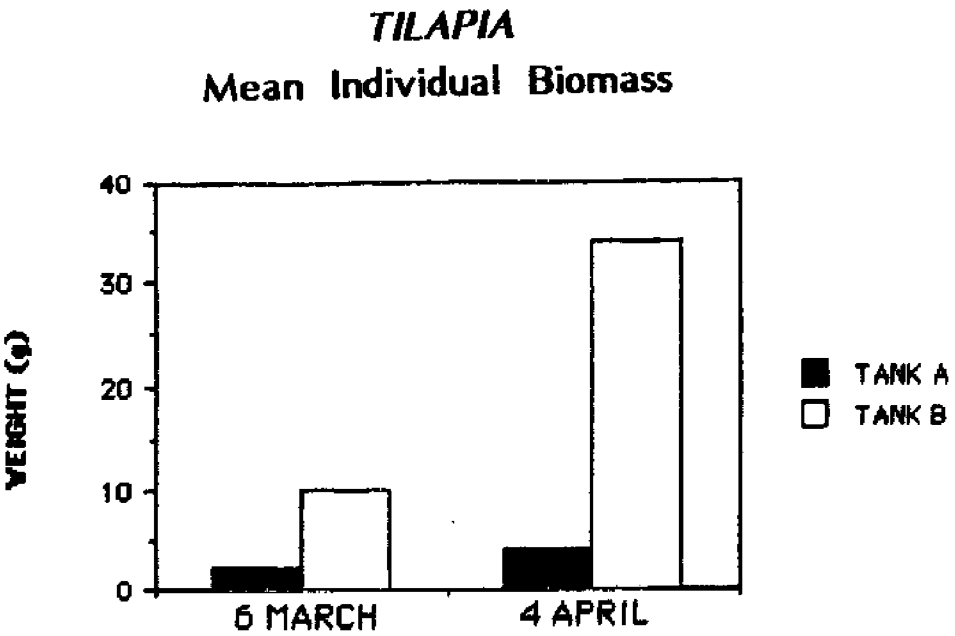

FIGURE 14: Changes in the mean individual biomass of the *Tilapia* in each tank.

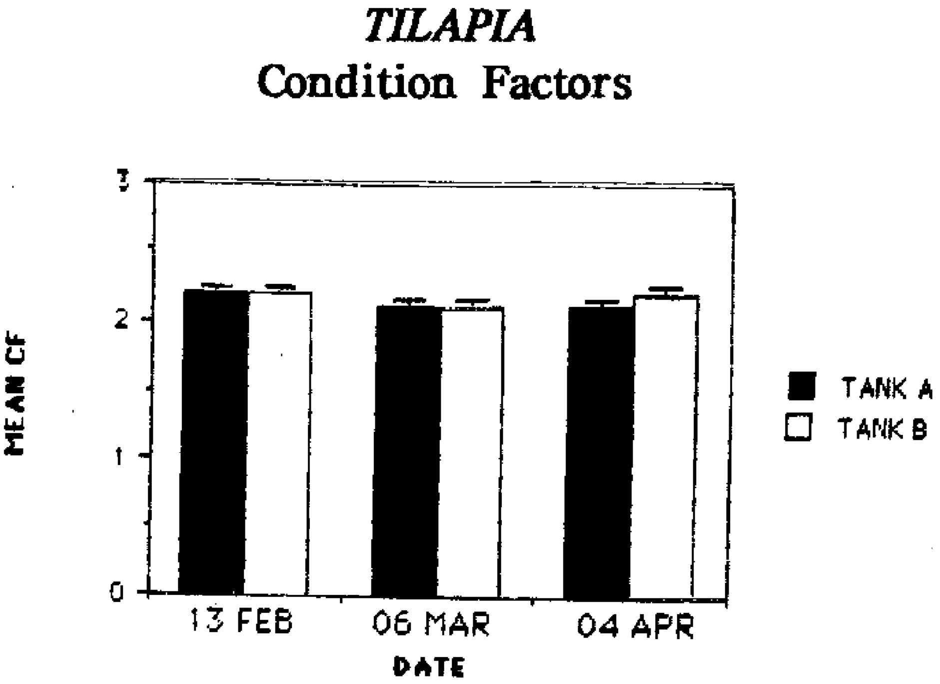

FIGURE 15: Comparison of condition factors based on a subsample of 24 individual *Tilapia* between Tanks A and B.

Plant Height

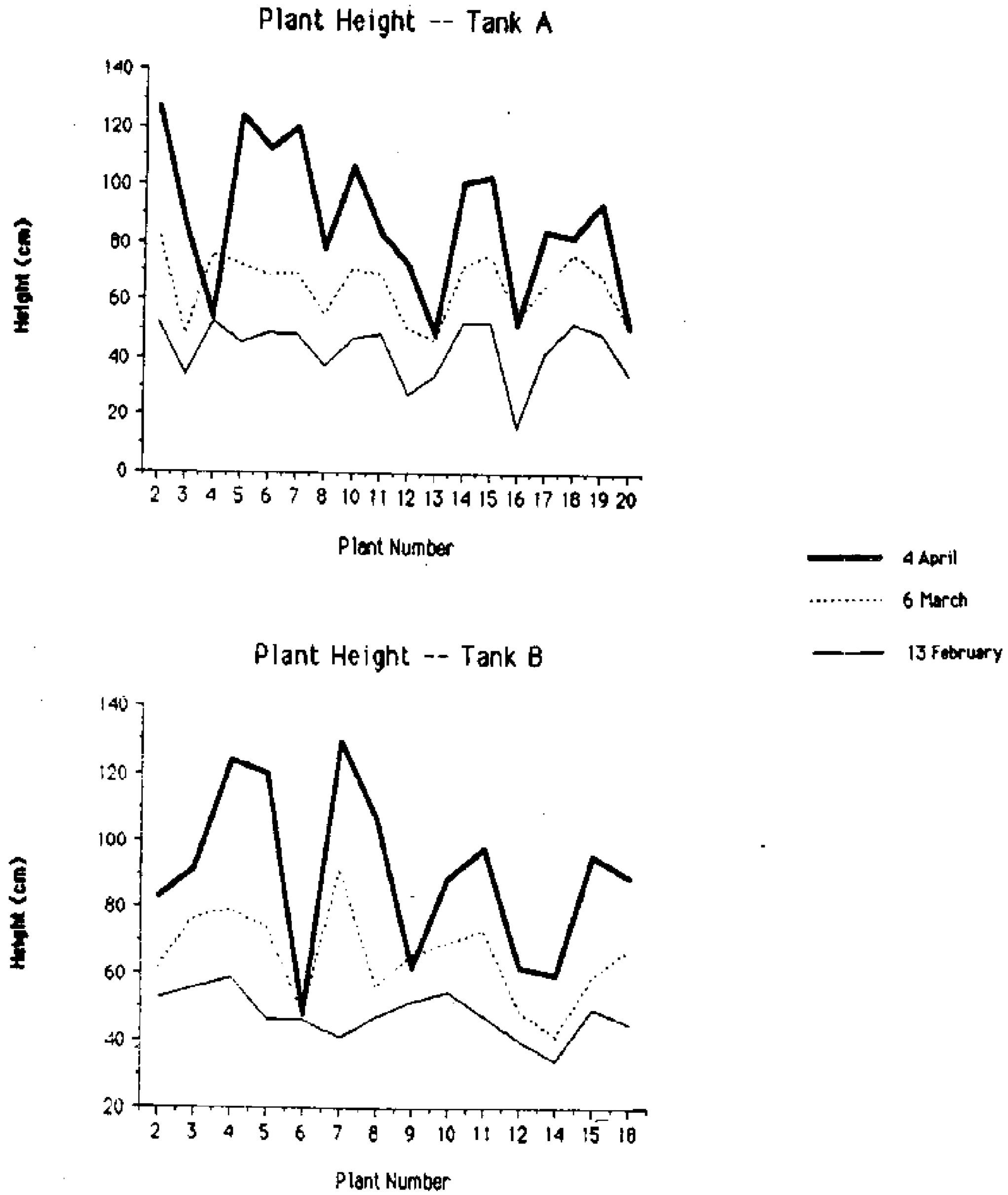

FIGURE 16: Height of the individual tomato plants in (a) Tank A and (b) Tank B during each month of the project.

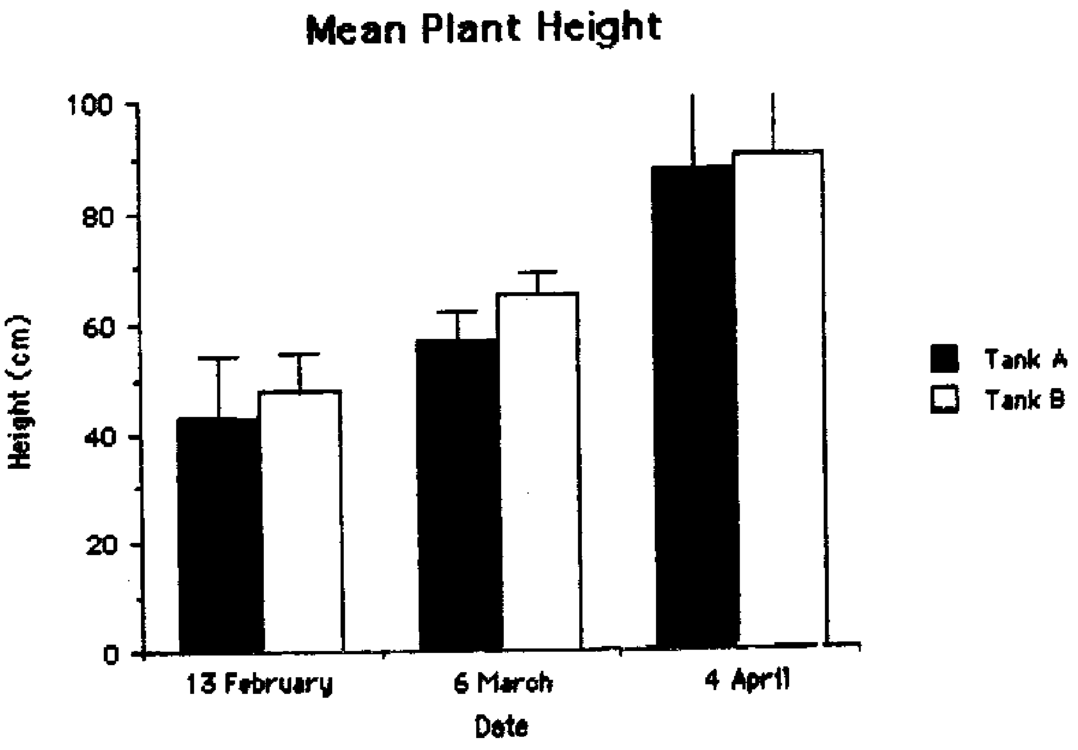

FIGURE 17: A comparison of the mean tomato plant height between Tanks A and B during each month of the project.

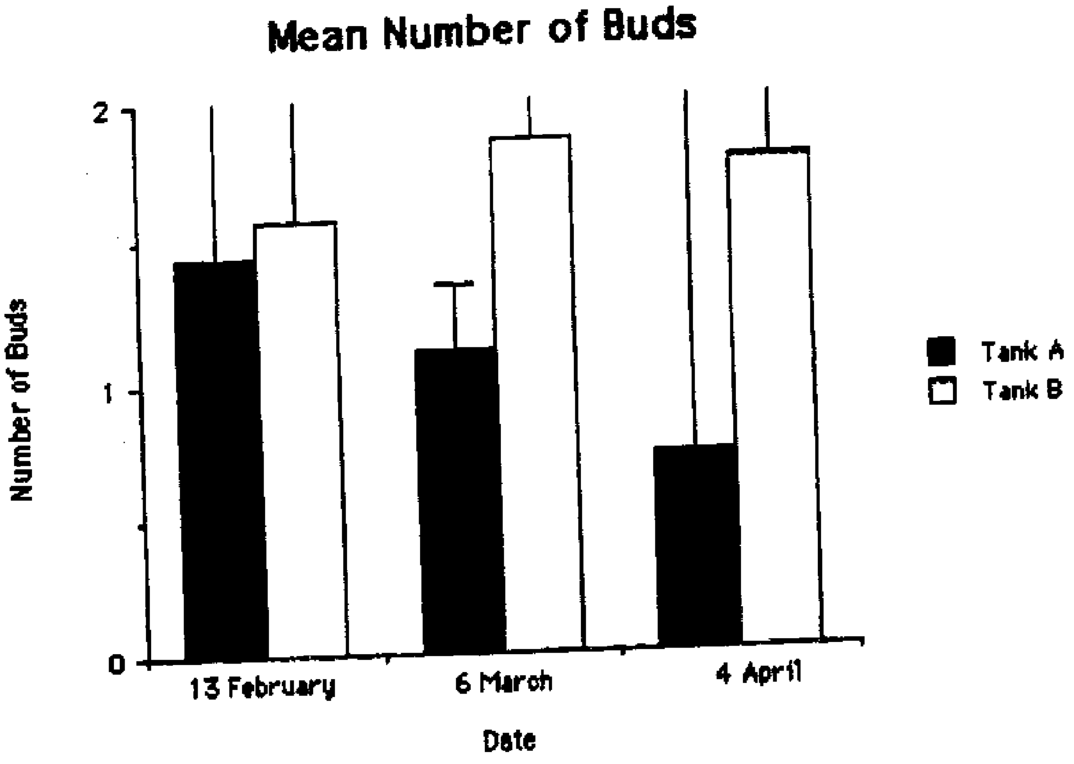

FIGURE 18: A comparison of the mean number of buds or flowers on each tomato plant between Tanks A and B.

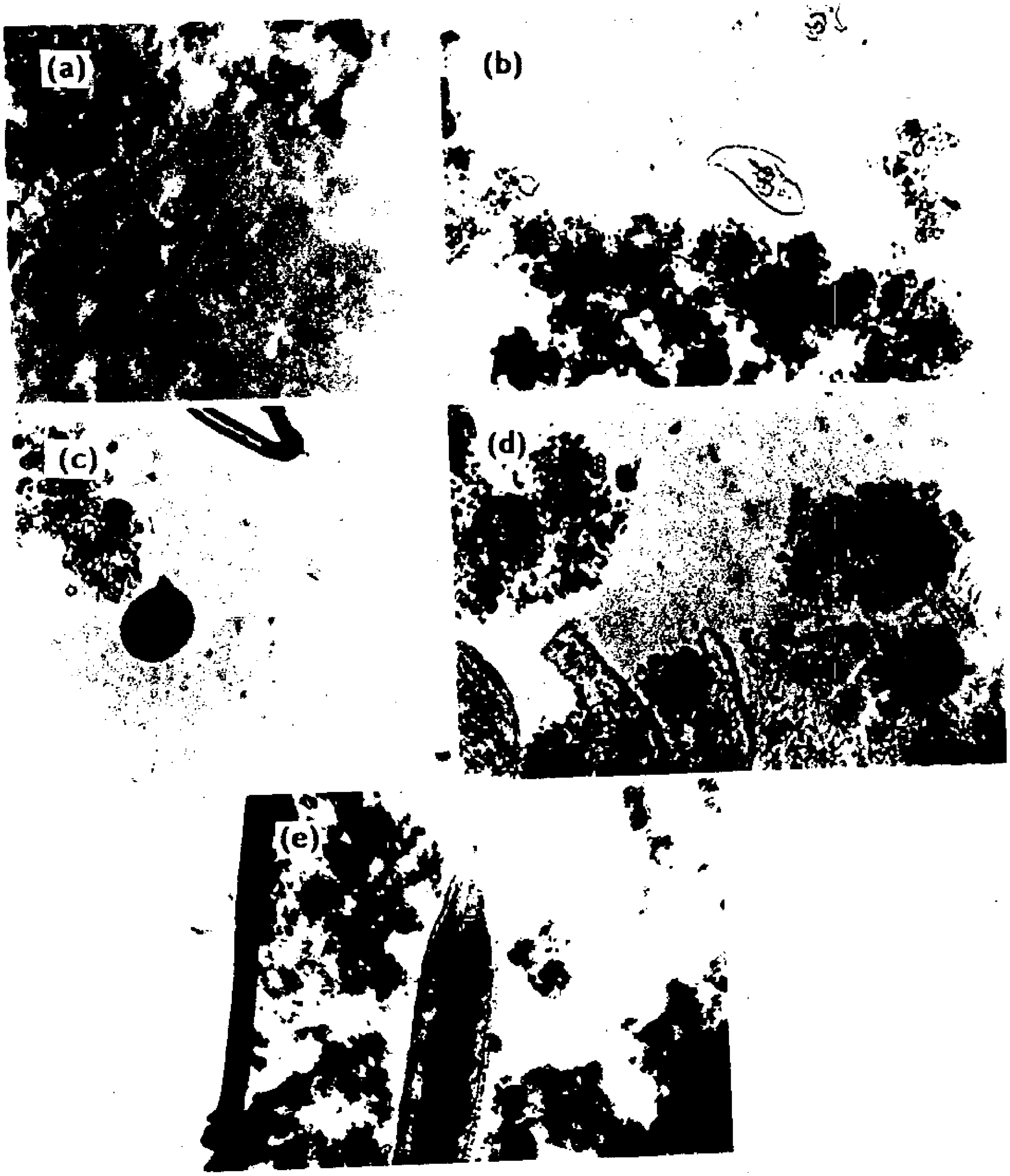

FIGURE 19: Photographs of larger members of the microbial community residing in the biofilm of Tank A and the gravel trough of Tank B. Representatives include (a & b) ciliates, (c) a shelled ameoba, (d) rotifers and (e) a small oligochaete seen in the gravel trough.

NITROGEN DYNAMICS
(Using an Aquarium Undergravel Filter)

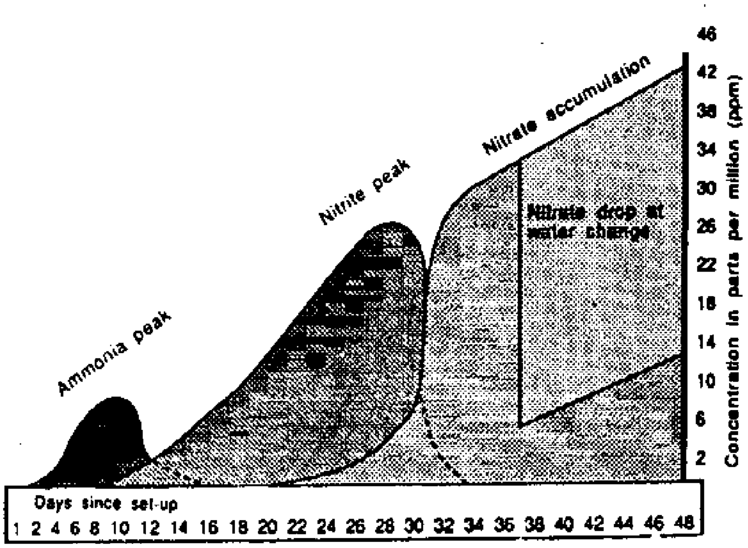

FIGURE 20: The typical patterns of waste nitrogen compounds (ammonia, nitrite, and nitrate) during the first 48 days of a new aquarium using a traditional undergravel filter (reprinted from Moe 1982).

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