THE INTEGRATED AQUACULTURE-VEGETABLE PRODUCTION SYSTEM

GOALS, PURPOSE AND OBJECTIVES

The production of high quality foods of substantial quantity on a consistent basis are essential to individual, cultural and national survival. As a prerequisite to genuine development, human populations require high-quality proteins, vitamins and minerals for proper nutrition. Fish and vegetables are excellent sources of these food groups. Therefore, there is a strong need for establishing a technology which allows for the efficient cultivation of these food groups while conserving freshwater and land resources.

The goal of the herein described technology is to assist the peoples of the arid and semiarid regions in their endeavors to increase food security and establish a year-round production capability to meet the demands of a rapidly increasing population. Increased annual growth rates in the agricultural sector will produce increases in agricultural incomes and on-farm capital formation. In addition, such changes will produce multiplying effects on rural and industrial employment. Reduction of unit costs of production will also tend to produce lower real food prices for consumers and more competitive prices for export commodities. This goal may be realized, in part, through the introduction and development of an intensive food production capability, specifically through establishing the innovative, scientifically proven, and repeatedly demonstrated technique refered to as the Integrated Aquaculture~Vegetable production System (IAVS) or IAVS technology in areas of humanitarian and environmental need. Because the IAVS technology is extremely conservative of the indigenous natural resources, especially of fresh water supplies, it is deemed most appropriate for: application in the regions with inadequate rainfall or other water-resources, areas with soils unsuitable for the practice of traditional agriculture metholologies, and locals with burgeoning or unsustainable levels of poplulation.

The combination of recirculatory aquaculture and of controlled environment vegetable production (IAVS) offers many efficiencies that neither production system has by itself. Benefits of integrating aquaculture and olericulture include:

a) intensive conservation of water resources through extremely high water-use efficiency in agricultural production,
b) makes productive of land/soils which are not suitable for traditional agriculture and reduces pressures on over-exploited landscapes,
c) economic utilization of low-cost agronomic and livestock "waste" as system inputs (use of livestock and aquaculture waste-products to produce food and reduce pollution) ,
d) intensive co-production of fish and vegetable crops (animal and vegetable protein, carbohydrates, vitamins and minerals) ,and
e) reduced operating costs relative to either production system in isolation (labor intensiveness in operation yet noncapital-intensive to implement).

The purpose of implementing this integrated food-production methodology (developing an socio-enviro-economically responsible capacity) is several fold:

a) to adapt specific operational and management techniques to meet local conditions, human need and national food-security,

b) to physically demonstrate and establish a comprehensive, enviromentally-benign food-production capacity,

c) to train potential implementors in its biologically effective and economically efficeint development process and reliable operation and supportive criteria.

d) to establish the sustained capacity to maximize food production efficiency per unit input of valuable natural resources.

This further includes:

a) increase employment opportunities for the disenfrachised and rural poor,

b) increase availability of high-quailty animal proteins in the diets of local citizens,

c) reduce seasonal fluctuations in availability of vegetable dietary products,

d) increase the caloric and nutritional content of dietary inputs for children which improves their capacity for cognitive development (leaidnf to effective, rewarding adulthood),

d) improve vitamin and mineral nutrition reduces susceptibility to disease and mitigates serverity of its effects, and

e) provide stimulus to local economies to include a potential to develop export capacity.

BACKGROUND OF INTEGRATED AQUACULTURE-VEGETABLE PRODUCTION

The culture of fish under captive conditions is not a new technology; the origins of aquaculture has been traced back into the pre-history of several regions. The physical principles and biological processes engaged in IAVS had been ostensively coalesced 5000 years ago in China. In the twentieth century, numerous technological developments have enabled the culture of an increasing number of species and allowed for production at increasing intensity. As a result, intensive aquaculture has become well-established in many areas of the world. However, most of the recently developed techniques require the consistent availability of large volumes of water in order to maintain water quality conditions which ensure economic levels of production. Because freshwater resources continue to rapidly become increasingly valuable worldwide, numerous research efforts have sought economic means of recycling a finite (limited) volume of water while maintaining productivity.

Aquaculturalists have known for a long time that some fish species (specifically Tilapias) gain weight more rapidly when grown at high stocking densities. Tilapia *(Oreochromis* spp. and *Sarotherodon* spp.; Cichlidaceae) are grown for human consumption in over 100 nations worldwide (Balarin and Haller, 1982; Pullen and Lowe~McConnell, 1982). Tilapia have a high market value potential in Egypt as well as many other parts of the world. But a major problem with intensively growing fish in closed water volumes has been the removal of their waste products in a cost efficient manner. Ammonia accumulation, generated by the metabolic processes/activity of fish, is of primary concern because it is toxic to fish and will reduce their survival and/or limit growth rate. Dissolved and suspended organic materials also accumulate rapidly in intensive aquaculture systems and must be removed for efficient fish production (Nair et al., 1985). Previously, this has been handled by filtering wastes mechanically (clarifiers, screening, sedimentation, etc.) and by the addition of new quantities of water or by replacing the water completely up to several times per day. Numerous investigators have tried to reduce water consumption by developing relatively complex recirculatory systems. Even in filtered recirculatory fish culture systems, nitrates and phosphates accumulate to unacceptable levels (Balarin and Haller, 1982; Watten and Busch, 1984).

During the 1980's, western researchers employed higher-plants, which assimilate nutrients for their growth through their root systems, to provide some final filtration before returning the water to the fish culture unit. The application of higher-plants, as a tertiary water purification element has been repeatedly demonstrated to provide some water quality improvements which has resulted in faster fish growth rates. Hydroponic vegetable production has been demonstrated to reduce nitrate and phosphate concentrations in recirculatory aquaculture water (Lewis et al. 1978a, 1978b, 1981; McMurtry 1988, 1990; McMurtry et al. 1987, 1990, 1993a, 1993b, 1994a, 1994b; Näegal. 1977; Nair et al. 1985; Rakocy 1989a, 1989b; Sanders, et.al., 1990 c; Watten and Busch 1984). However, plants grown in filtration systems which remove the suspended organic waste products of fish production prior to plant application have not been very productive.

Most, if not all, previously reported integrated fish-vegetable systems have removed the suspended solids from the water by sedimentation in clarifiers prior to plant application (Rakocy, 1989 b). Removal of the solid wastes by sedimentation has resulted in insufficient residual nutrients for plant growth. Plants grown in such systems have typically exhibited gross nutrient deficiencies, because much of the nutrient has been stripped from the water. Acceptable fruit yields have previously only been achieved with substantial supplementation of plant nutrients (Lewis et al., 1978, 1981; Rakocy, 1989 b). All of the nutrient elements required for plant growth are found in the fish wastes products, but most of these elements are in chemical forms which are not water soluble. The non-soluble nutrients (elements) are removed during the clarification/sedimentation process and therefore are not available to support plant growth. The successful management of integrated systems requires that concentrations of all required nutrients be maintained in the appropriate chemical forms, in order to maximize both fish and plant yields (Rakocy, 1989 b).

In 1985, researchers at North Carolina State University (NCSU) asked the question "why is all the settling, filtering, and nutrient-stripping necessary"? They reasoned that if plants were grown in sand culture (sand-beds), perhaps the sand would mechanically filter the solid waste products from the water as well as provide a substrate (environment) for the nitrifying (and other) bacteria which convert both soluble and non-soluble aquaculture waste fractions into forms which can be utilized by higher plants. This would sufficiently clean the water to permit recycling back to the fish culture unit. By making the nutrients in the suspended solid fraction of the fish wastes, in addition to the soluble (dissolved) nutrient load of the water, available to the plants, the plants would have more nutrients for growth. However, concern about toxic concentrations of soluble ammoniacal-nitrogen still remained. In nature, certain soil bacteria rapidly convert ammonia to nitrate. Nitrate is relatively non-toxic to fish and the preferred form of nitrogen for plants. An inoculum of these nitrifying bacteria was added to the ‘sand-beds’. The ‘sand-bed’ provided the substrate for all of the terrestrial organisms (bacteria, algae and plants) and, collectively, these elements are referred to as a ‘biofilter’. The combination of the aquatic and terrestrial environments / organisms constitutes a complete, interdependent, and symbiotic ecosystem.

The NCSU researchers found that this technique did function to effectively clean the aquaculture water. The ammonia level in the water was reduced by 50% with each pass through the ‘sand-bed’. They found that the ‘sand-bed’ was indeed a biological filter, because the bacteria, algae, and higher plants were critical to the system operation (to the ecosystem). When they operated the systems without plants actively growing in the ‘sand-bed’ (biofilter) to act as a living (active) buffer and nutrient-sink, the pH of the water rapidly dropped to levels dangerous to fish survival while ammonia and nitrite concentrations increased to toxic levels. The plants effectively removed all required nutrient elements from the water and from the biofilter (microbial conversions of solid waste fraction). All nutrients were assimilated by the plants in sufficient quantities and in proper proportions to result in rapid growth and high yield rates. When active plant growth was maintained in the biofilter, the pH of the aquaculture water stabilized around pH 6.0, and ammonia, nitrite and nitrate levels were maintained within a range sufficient to provide for excellent fish growth rates. Each 1.0 kg of fish weight gain provided sufficient quantities of all required plant nutrients to sustain 2 tomato plants yielding 5-7 kg of fruit per plant over 3 months.

Algae, which grow on the surface of the biofilter, also provides an important role in stabilizing the nutrient concentrations of the water. Algal populations tend to grow rapidly when the higher plants are young and not capable of utilizing all of the available nutrients. The algae largely disappear as the plants grow older (larger) and therefore assimilate an increasing proportion of the nutrient load. The algae provide a self-regulating nutrient sink or buffer which attenuates fluctuation in nutrient concentrations (or biofilter loading) during intervals of reduced plant growth (i.e. alga assimilate, store, and release Phosphorus compounds).

A significant benefit in this approach to integrated aquaculture is that it confers the ability to utilize a given water volume from 120 to 300 times rather than the 1 to 3 times normally associated with other recirculating systems. This increased capability to reutilize the water in fish production translates to a 100- fold increase in fish yield per unit volume of water consumed (plus the production of the vegetable crops). In most recirculating aquaculture systems, the water may be recycled up to 3 times before concentrations of ammonia and/or other forms of nitrogen reach toxic levels. Operators of such systems schedule the regular replacement of ‘soiled’ water with a fresh water input at a rate of 100 to 300 percent per day. In the IAVS technique, the ‘soiled’ water is not actively replaced but repeatedly filtered and returned to the fish culture tanks. Water consumption in the IAVS technique is a function of the combined rates of plant transpiration and evaporation from the biofilter surface following irrigation. In other words, the fish production component is not a significant source of water consumption. The rate of water input (replacement of evapotranspiration losses) in the IAVS technique ranges from 1 to 3 percent of system capacity per day. As an illustrative example, the recirculating aquaculture facility at The Land Pavilion of EPCOT Center (Walt Disney World, Orlando Florida.) utilizes 1100 cubic meters of fresh water inputs annually for each 1.0 cubic meter of system capacity (personal communication). By contrast, the IAVS technique requires only 11 cubic meters of water per year for each 1.0 cubic meter of system capacity (at a 3 percent per day rate of loss).

The relative ratio of water volume to biofilter volume (of fish production to plant growth) is an obvious and important consideration in successfully applying this technique. As size of the biofilter per fish tank volume is increased, the yield of tomato (for example) decreases from 27 to 19 kg per square meter per crop, but the fish grow 20% faster. This results from a reduction in nutrient availability per plant but an increased filtration capacity (cleaner water) for return to the fish with increasing biofilter size (increasing plant number). A broad range of vegetable species have been shown to assimilate sufficient quantities of all required elements derived solely from the fish waste products, and there have been no nutrient toxicities seen. Yield responses are generally favorable over a relatively wide range of tank:biofilter ratios but varies by species. Fish yield rates tend to be relatively suppressed at low plant population densities per unit of fish cultured.

Most aquaculture techniques which recycle water have provided for a constant water flow. Accomplishing this constant water movement requires a substantial energy input. In the Integrated

Aquaculture~Vegeculture System (IAVS) developed at NCSU, the movement of water between the aquaculture 'tank' and the biofilter is not conducted on a constant flow basis. The water is moved (pumped) intermittently during the daylight hours in volumes sufficient to flood the biofilter. The sum of the water pumping intervals in the technique developed at NCSU is less than 2 hours per day. The energy demand of this technique is approximately one-twelfth the energy requirement of other recirculating aquaculture techniques.

In the IAVS system, once the biofilter is flooded during a pumping cycle, the withdrawal of waste-laden aquaculture water ceases and the biofilter is allowed to drain the cleansed water back into the 'tank'. This scheduled water movement within the biofilter has been termed "reciprocating" although "intermittent" may be a more accurate description.

Reciprocating biofilters (RBF), which alternatively flood and drain, provide a) uniform distribution of nutrient-laden water within the filtration medium during the flood cycle and b) improved aeration of the biofilter due to the atmosphere exchange created by each dewatering. This 'flood-and-drain" water movement cycle benefits both nitrifying bacteria and plant roots (Lewis et al., 1978; Paller and Lewis, 1982; Nair et al., 1985; Rakocy, 1989 a, 1989 b; McMurtry et al., 1990 a, 1991 a). The increased availability of oxygen to the nitrifying bacteria improves their ability to convert ammoniacal-nitrogen to nitrate (facilitates the nitrification process). Nitrification is limited by oxygen concentrations lower than 2 mg per liter (Nair et al., 1985) and the complete oxidation of 1.0 mg of NH_3- N requires 4.6 mg of oxygen (Kaiser and Wheaton, 1982).

Benefits of integrating aquaculture and olericulture are: l) intensive conservation of water resources, 2) utilization of aquaculture "waste" products to produce food and reduce pollution, 3) intensive production of fish protein and vegetable crops and 4) reduced operating costs relative to either production system in isolation (McMurtry et al. 1987, 1990 a, 1991 d; Sanders and McMurtry, 1988; Sanders, et.al. 1990.). The constraints of water supply, soil type and land availability do not limit the use of recirculating systems as occurs in pond or cage aquaculture (Rakocy 1989 a). Water consumption in recirculatory integrated systems which culture tilapia is less than 1% of that required in pond culture techniques to produce equivalent yields (Rakocy 1989 b; McMurtry, et. al., 1990 a, 1991 a). Such a symbiotic system is applicable to the needs and requirements of arid or semi-arid regions where fish and fresh vegetables are in high demand (Nair et al., 1985; Rakocy, 1989 b; McMurtry et al., 1987, 1990 b, 1991 d).

Our data indicates that one can realize both fish and fresh produce production sufficient to feed a family of four, year-long, on a plot barely large enough to park an automobile. Yields attained in Raleigh, NC indicate that this automobile-sized space could produce 150 kg of fish and 1,100 kg of vegetables per year which assumes a periodic harvest as both the fish and vegetables reach appropriate size.

This co-production system is a significant innovation relative to common aquaculture practices. The IAVS technology was specifically developed for application in the arid and semiarid regions, such as in Africa and the Near East, where water and/or land resources are dominantly limiting to food production. It is a tightly-coupled, virtually symbiotic, method of producing both fish and vegetables on a small area of land, using extremely conservative water-management practices. The IAVS is a state-of-the-art intensive production methodology which substantially enhances both resource utilization efficiency and economic productivity in agriculture through the management of an intentional ecosystem.

Two applications of this technology are apparent. One is as a small-holder activity using local inputs, providing food self-sufficiency plus some surplus for the cash market. A second application is as large-scale commercial enterprises to service centers of population. The IAVS holds substantial promise for providing limited-resource farmers and urban families an opportunity to augment both the family diet and income. The prospect of producing meaningful quantities of nutritious food with minimum consumption of valuable water resources and in a manner which has indiscernible adverse impact on the local environment is significant. The additional characteristic of being able to do this, at otherwise rigorous sites, with local inputs and unsophisticated managerial skill renders the technique doubly attractive.

TECHNICAL OVERVIEW

Production of freshwater finfish and ‘organically growth’ vegetables was linked in a closed recirculating water system (McMurtry 1987, 1990; McMurtry et al. 1990, 1993a, 1993b, 1994a, 1994b; Sanders and McMurtry, 1988; Sanders et.al. 1990). Hybrid tilapia *(Oreochromis mossambicus* (Peters, x *O. niloticus* (L.)) were cultured in in-ground tanks and fed a feed ration with a 32% protein content and no vitamin or mineral supplementation. Tomato *(Lycopersicon esculentum* Mill. ‘Laura') was grown in summer 1988, cucumber *(Cucumis sativus* L. ‘Fidello') in fall 1988, and tomato ‘Kewalo' in spring 1989 in a Raleigh, N.C. greenhouse. (Subsequent research has evaluated various multicrop combinations and replicated species rotations.) Four tank to biofilter volume ratios were studied. Plants were grown in biofilters at 4 plants m^{-2} and irrigated 8 times daily with water from the associated fish tank. Biofilter drainage returned by gravity to the fish tanks. Each system received identical nutrient inputs and each plant received an equal quantity of water at each irrigation event.

The aquaculture water was periodically moved through a biofilter composed of sand, bacteria, algae, and vegetable crops. This co-production technique was found to be extremely efficient in the utilization of water. Through water purification and reuse, this recirculating system consumed less than 1% of that used in pond culture to produce equivalent fish yields while simultaneously producing a second crop of vegetable. Depending upon the crop, season, and the biofilter to tank volume ratio, this technique permits from 120 to over 300 crop applications with each unit volume of water. Fish yields ranged from 50 to 70 kg per cubic meter of water per year (0.41 to 0.57 lb/gal/yr) and tomato yields exceeded 6.8 kg (15 lb) per plant. Feed conversion ratios for fish of average market size (0.25 kg) ranged from 1:1.1 to 1: 1.3.

Fish metabolites, uneaten feed, and dead algae were converted by biofilter microbial populations into nutrient forms utilized by higher plants (vegetable crops). Numerous vegetable species have been successfully grown with this technique. Biological filtration, aeration of the water, mineral assimilation by the vegetable crops and the addition of water equal to evapotranspiration losses maintained water quality for excellent growth rates of tilapia. Nitrogenous compounds, which limit production in most recirculatory systems, did not approach toxic levels in this system because these were extracted by the plants. Dissolved oxygen levels, make-up water, fish biomass increases and fish growth rates increased with biofilter volume. Total ammoniacal-N, NO_2, and NO_3 concentrations decreased with increasing biofilter volume. Water pH declined rapidly when the system was operated the without plants growing in the biofilter. When plants were actively growing in the biofilter, the water pH remained stable at approximately pH 6.0 when the rate of fish-feed inputs were not excessive.

The aquaculture “wastes” provide the plants with all required nutrients in adequate proportion. Yield rates of vegetable crops have been consistently high, substantially exceeding US open-field yields, and compare very favorably with yield rates in other intensive production methodologies. Fruit yields of tomato and cucumber have ranged 5 to 10 fold of average US fresh-market field yields and were far superior to those achieved in previous integrated aquaculture methodologies. Total fruit yield increased but yield per plant decreased with increasing biofilter volume. Fruit yields and fish biomass increase per plant declined with increasing biofilter volume. Fish growth associated with the largest biofilter was 120% of that associated with the smallest biofilter.

All plant nutrients were assimilated above deficiency levels. Tissue concentrations of N,P,K and Mg were not limiting. Calcium was low and S was high when the sole nutrient source was fish waste products derived from the specific feed formulation utilized. Micronutrients were assimilated in excess of sufficiency, but no toxicity symptoms were seen. Irrespective of fruit yield, the metabolic products of each 1.0 kg increase in fish biomass provided sufficient nutrients for 2 tomato plants for a period of three months. Under reduced growth rates (and parallel feed input rates) typical of mature fish, K became limiting. Alternations in fish-feed composition (mineral nutrient content which better meets plant requirements and still remain within the range of fish needs were suggested (McMurtry et al. 1991 c).

Caloric content of the increase in fish biomass per liter of total water decreased while that of tomato increased with increasing biofilter volume. Calories per liter of water used in the combined yields did not differ by treatment. Total protein production per liter of water used decreased with increasing biofilter volume. Both caloric value and protein production in the combined outputs increased with biofilter volume irrespective of water consumption. Each liter of water employed can produce, in fish and fruit, 0.7 grams of protein,7 kilo-calories food-energy, and most essential vitamins. This level of production is at least an order of magnitude more efficient in the use of water than open-field production in the U.S. (i.e., poultry and corn). The IAVS technology was expressly developed for and is eminently applicable to the requirements of regions where water and/or land is limiting to food production.

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