

The design, management and production of a recirculating raceway system for the production of marine shrimp

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Abstract

Despite continuing problems with disease outbreaks and environmental concerns over effluent pollution and land usage, world shrimp farming continues to expand. Although traditional pond production systems will continue to be the dominant driving force in aquaculture expansion, there is continued interest in alternate production systems. The use of high density, water reuse systems is one alternative to conventional pond production systems which addresses restrictions associated with environmental regulations and user conflicts of coastal land and water usage. This paper reports on techniques which have been developed for the production of marine shrimp in recirculating raceway systems and typical results which have been observed over a 6-year production period. Both bait shrimp (*Penaeus setiferus*) and food shrimp (*P. vannamei*) have been produced with final biomass loads as high as 10 kg/m³ utilizing 100–120-day and 160–175-day production cycles, respectively. Results from multi-phase growout are most promising and indicate that this may be a suitable mechanism to optimize biomass loading of the culture system. Although the economic viability of recirculating production systems for bait and food size shrimp have yet to be proven, the consistent results of production, low water usage and ease of waste management are encouraging and warrant further economic and marketing evaluations. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Increased demand for seafood combined with declining catches of marine fish and shellfish has stimulated the expansion of world aquaculture to a US\$39.83 billion (ex-farm) world wide industry in 1994 (FAO, 1996). Not only has this led to an increase of conventional farming systems, but there is also a strong shift toward high-density, highly productive systems which maximize biomass output per unit investment (Rosenthal and Black, 1993). These smaller, intensive systems are essential for temperate climates, where sufficient water temperatures are not available year round, and in commercialized areas where land and labor costs are high. Regardless of location or intensity of the culture system, marine aquaculture can only be successful if it is cost effective, ecologically sustainable, socially responsive and scientifically sound.

Aquaculture simultaneously impacts and is impacted by the aquatic environment. Consequently, the aquaculturist and the public are both concerned about the environmental impacts of confined feeding operations on the aquatic environment. Effluents from confined feeding operations for terrestrial and aquatic animals may lead to or contribute towards eutrophication and oxygen depletion of the surrounding waters, making them less suitable for aquaculture and other purposes (Folke and Kautsky, 1991). The potential problems associated with over-development and unregulated discharges of waste products (industrial and agricultural) into estuarine environments and their effects on culture systems are exemplified by reduced production and/or the complete elimination of commercial shrimp culture operations due to disruption of estuarine ecosystem biota. Examples include Taiwan, northern Thailand, China and Ecuador (Twilley, 1989; Boyd and Musig, 1992; Liao, 1992; Chen et al., 1993). If marine aquaculture is to be encouraged, methods to mitigate adverse environmental effects of aquaculture must be developed and implemented.

Land based marine culture systems are primarily found in rural areas and utilize traditional pond culture techniques. As an alternative to conventional pond culture, the use of high density, water reuse systems would address restrictions associated with environmental regulations and user conflicts of coastal land and water sources. Intensive water reuse systems allow freedom from site limitations, reduction of labor per unit production, improved environmental control, increased product quality and availability, and facilitate the control of stock and effluent management (Rijn and Shilo, 1989; Lee, 1993).

The University of Texas at Austin, Marine Science Institute, Fisheries and Mariculture Laboratory, has employed water reuse systems for over 20 years for both research and intensive production of fish and shrimp. The basic recirculating system and procedures utilized for the intensive production of shrimp were originally described by Arnold et al. (1990) and Reid and Arnold (1992), respectively. This simple system utilized direct stocking of post-larvae into the raceway culture chamber. Airlift pumps and gravity flow circulated water through the culture chamber and vertical screen filter plates served as the substrate for the biological filter. Although this system was successful it had several disadvantages which

included a considerable labor requirement to maintain the biological filters and an inefficient use of culture space or biomass loading. Consequently, several alterations have been made in system design and operational procedures to increase the efficiency of waste removal, minimize labor requirements and maximize biomass loading. This paper reports on the methodologies which have been developed for the production of marine shrimp in recirculating raceway systems and typical results observed over a 6-year production period.

2. Methods

The following is a description of the culture systems and procedures which have been utilized for the intensive culture of *Penaeus setiferus* and *P. vannamei* at The University of Texas at Austin, Marine Science Institute, Fisheries and Mariculture Laboratory, Port Aransas, TX, USA. A summary of the design criteria for each system is presented in Table 1.

2.1. System layout

2.1.1. Nursery system

The nursery system utilized for post-larval (PL) growout was a closed-loop recirculating system with the following flow scheme: culture tank → settling area with foam fractionation → biological filter → settling area → recycle to culture tank. The culture system consisted of a 3.65-m diameter circular fiberglass tank designed to contain 10 m³ of seawater connected to a fiberglass-coated plywood filter box (internal length, width and height of 1.82 × 0.65 × 0.61 m). The filter box was gravity fed with settling areas prior to and after the filter substrate which consisted of 0.283 m³ of 1.6-cm Flexrings[®]. The filter substrate was a polypropylene packing material with a surface area of 344.7 m²/m³ (105 ft²/ft³; Aquatic Ecosystems, Apopka, FL). Water was circulated at rates up to 40 l/min utilizing a 2-inch airlift pump with gravity feed. The culture chamber was equipped with an additional 2-inch PVC airlift to enhance circulation, three air diffusers (porous plastic 0.2–0.6 cubic feet per minute (CFM)/ft) and a 2-inch drain line fitted with a 4-inch PVC well head pipe to screen out post-larvae. A small counter current foam fractionator was placed in the settling chamber to help remove soluble surface active materials. A 1/10 hp submersible centrifugal pump equipped with venturi injector and a screened intake was available for addition to the system to allow the introduction of supplemental oxygen during the final week of production and during harvesting.

2.1.2. Raceway systems (25 and 35 m³)

Two sizes of raceways, each sharing a common footprint, were utilized (Fig. 1). Each system consists of three separate tank components: fiberglass raceway (internal length, width and height of 13.72 × 2.44 × 0.91 or 1.22 m); fiberglass reinforced plywood filter box (1.22 × 1.17 × 1.22 m) containing a rotating micro-screen filter; fiberglass filter box (4.77 × 1.22 × 1.22 m) divided into four equal compartments

Table 1
Preliminary design criteria for the described culture systems

	Culture chamber ^a	Micro-screen ^a	Settling and filtration ^a	Flow rate (l/min)	Filter area (m ²)	Nitrification capacity ^b (g N/day)	Feed capacity (kg/day) ^c	Oxygen demand ^d (kg O ₂ /day)
Circular tank	10		0.6	40	97.5	58.5	1.95	2.2
Raceway	25	1.0	5.0	280	401.6	240.9	8.0	10.2
Raceway	35	1.0	5.0	280	401.6	240.9	8.0	10.2
Raceway	72	2.0	17.0	720	836.6	502.0	16.7	21.2

^a Water volume (m³) which each component is designed to hold.

^b Calculated based on a nitrification capacity (ammonia detoxification efficiency) of the biological filter of 0.6 g total ammonia nitrogen (TAN) per square meter of filter media surface area.

^c Calculated based on 30 g TAN per kg of feed.

^d Calculated based on 1.14 kg oxygen per kg of feed.

consisting of a foam fractionation/settling chamber, biological filter (two compartments) and secondary settling chamber/ozone reactor. Each system was set up in an equivalent configuration and only differed in the depth of the culture tank and subsequently, the volume of culture water (25 vs. 35 m³). Both systems were run with at least 12 cm of freeboard and had a 2.5-cm mesh net covering the culture chamber.

For each system, the effluent water from the culture chamber is discharged into the micro-screen barrel. Suspended solids are collected on the rotating screen and washed into a catch basin for discharge. The filtered water is then air-lifted out of the rotating micro-screen filter box and into two foam fractionators. The water passes through a settling chamber, two reverse flow biological filter chambers and a secondary settling chamber/ozone reactor. After treatment, the water is pumped back into the culture chamber at a rate of up to 280 l/min.

Aeration to the raceway (via four porous plastic diffusers, filter box aerators and airlift pumps) is provided by a regenerative blower. The biological filter consist of two chambers each containing 0.9 m³ of 5.8-cm Lanpac[®] packing material (Lantec Products, Agoura Hills, CA) and supplemental aeration. The packing material is made of polypropylene with a nominal size of 5.8 cm, void fraction 89%, and geometric surface area of 223.1 m²/m³ (68 sq ft/cu ft). Filtered water entering the secondary settling chamber was treated with ozone (2–4 cubic feet per hour (CFH)). Ozone was produced with a corona discharge ozone generator (Innovative Water Technologies Corporation, San Antonio, TX) with oxygen feed. Ozone and oxygen were injected via venturi aspirators powered by a 1/10 hp pump (either 1/10 hp Teel submersible centrifugal pump, Dayton Electric, Chicago, IL, or 1/10 hp magnetic drive pump, Little Giant Pump, Oklahoma

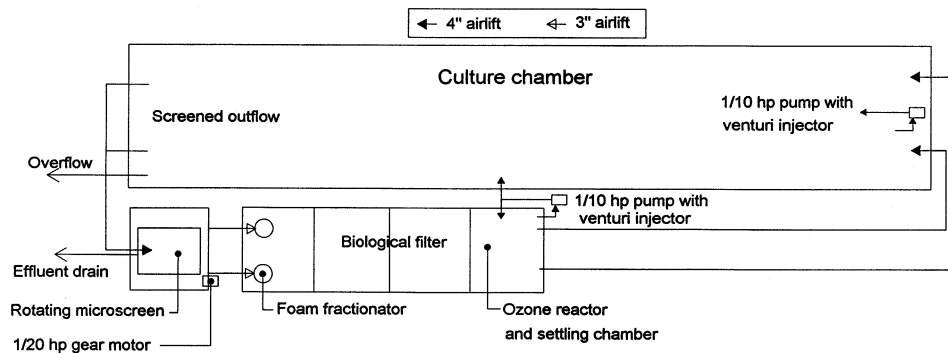


Fig. 1. Diagram of the 25- and 35-m³ semi-closed recirculation systems consisting of culture chamber, micro-particulate removal system, biological filter and oxygen/ozone injection. Flow scheme: culture chamber → micro-screen → foam fractionation → settling area → biological filter → settling area with ozone injection → recycle to culture chamber.

City, OK). Additional oxygenation of the culture chamber was obtained by adding a second pump which was equipped with two venturi aspirators and a screened intake.

2.1.3. Micro-screen filter

The rotating micro-screen filter was fabricated in-house and was mounted in a fiberglass reinforced wooden box. Nitex screen (100 μm , mesh 3-100/47; Tetko, Briarcliff Manor, NY) was affixed with silicon sealant to the outside of a 55-gal plastic barrel which was mounted horizontally in the box and is driven by a 1/20 hp gear motor rotating at 6 rpm. The barrel was prepared by drilling 12 rows of five equally spaced 4.5-inch holes (one row of five holes was cut out to allow the insertion of the internal catch basin). At the center of one end of the barrel, a 4.5-inch hole was drilled to accommodate the 4-inch PVC intake pipe and on the opposite end of the barrel, a stainless steel 3/4-inch drive shaft with synchronous drive gear belt pulley was attached via a mounting plate. The barrel rotated on an axis which consists of the intake pipe inserted through the wall of the barrel and the stainless steel shaft inserted into a self-lubricated flange bearing mounted on the opposite side of the tank.

Effluent water from the culture chamber or raceway entered the barrel by airlift assisted gravity flow (10–15-cm head) through the 4-inch line. Water then passed through the screen into the barrel's box where it was airlifted into a settling chamber. Solids were removed from the screen on a continuous basis by a series of salt water spray jets (90° Jet Nozzle, Submatic Irrigation Systems, Austin, TX). The solids were carried away from the screen by the water jet and deposited into the internal catch basin which then drains from the system. Currently, we utilize two spray bars each containing 10 spray nozzles. One spray bar runs continuously with fresh sea water originating from a header tank and utilizes 7–8 l/min. Approximately, 29% of this water leaves the system via the drainage basin with 71% spilling into the system. The second spray bar runs intermittently (1–2 15-min washes per day) with chlorinated freshwater under high pressure.

2.1.4. Raceway system (72 m³)

A schematic diagram of the system is presented in Fig. 2. The raceway system was constructed utilizing a concrete bottom and side walls constructed from 4-inch \times 4-inch posts, 2-inch \times 4-inch headers and plates, with 3/4-inch plywood sides. A 16-mm liner core of high density polyethylene woven material with low density polyethylene coating on either side (AW16-16A, Yunker Plastics, Lake Geneva, WI) was then fitted to each compartment. This raceway system consists of six separate components: culture chamber (internal measurements for length, width and height are, 27.43 \times 2.97 \times 1.07 m); two fiberglass coated plywood boxes (1.22 \times 1.17 \times 1.22 m) each containing a rotating micro-screen filter; common settling chamber (6.90 \times 1.11 \times 1.07 m); three filter boxes (2.13 \times 1.19 \times 1.07 m) each containing 1.25 m³ Lanpac[®] packing material, foam

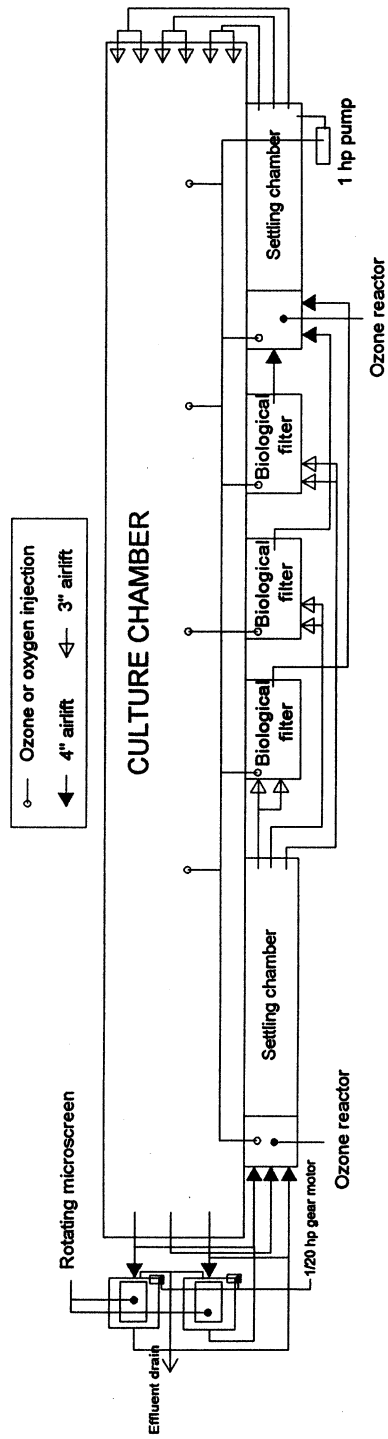


Fig. 2. Diagram of 72-m³ raceway system consisting of culture chamber, micro-particulate removal system, settling chamber, biological filters and ozone reactor and final settling chamber. Flow scheme: culture chamber → (micro-screen → foam fractionation) or (foam fractionation) → settling area → biological filter → ozone reactor → settling area → recycle to culture chamber.

fractionator and ozone reactor ($1.33 \times 1.19 \times 1.07$ m); and clarifying/degassing chamber ($4.01 \times 1.19 \times 1.07$ m). On three sides of the culture chamber a 30-cm high plastic mesh fence extends above the sidewall. On the fourth side movable nets hang vertically along the length of the culture chamber.

Water is moved throughout the system by a series of airlift pumps and gravity flow at a rate up to 720 l/min. Effluent water leaving the raceway can be directed through the micro-screen system or directly into the settling basin. All water, either from the micro-screens or directly from the raceway, enters a common settling chamber. Water entering the settling chamber is exposed to a stream of ozone, which is introduced to facilitate flocculation of particulate material. Suspended solids which have settled are discharged by 3-inch drain line running along the bottom of the settling chamber or by manual siphoning. The settled water is then airlifted into each of three parallel biological filters. Water exits each filter box and enters a common foam fractionation/ozone reactor chamber. Ozone is introduced into the reactor via three venturi aspirators with ozone feed. A maximum of 18 CFH of ozonated oxygen was utilized. The treated water then travels via a common 6-inch PVC pipe into the retention chamber for degassing and final settling. The treated water is then airlifted into the top of the culture chamber at a rate of 720 l/min. Gas exchange and resuspension of settled solids is facilitated by 10 porous plastic diffusers spaced throughout the culture chamber.

2.2. Culture procedures

2.2.1. Nursery phase

Post-larvae (PLs) were obtained from commercial suppliers (Harlingen Shrimp Farms Unlimited, Los Fresnos, TX and Lone Star Hatchery, Port Isabel, TX) with a history of providing high health shrimp. The results from two populations of *P. setiferus*, obtained for the production of bait shrimp for winter sale, and three populations of *P. vannamei* PLs for the production of food size shrimp are reported.

Upon arrival, PLs were sampled for disease screening and estimation of initial weights. Post-larvae were then acclimated to the culture conditions utilizing partial water exchanges (a rate no faster than 4°C or 4 ppt salinity change per hour) to equalize environmental parameters. After acclimation, the PLs were stocked into the nursery system at densities ranging from $582/\text{m}^3$ to $8300/\text{m}^3$ (Table 2). The nursery phase ran for 21–34 days. *P. vannamei* PLs were offered approximately, 100 newly hatched *Artemia* nauplii/PL/day for the first week of culture and then intermittently during the second week. *P. setiferus* post-larvae were fed *Artemia* nauplii throughout the nursery phase. The PLs were also offered commercial shrimp feeds containing 45% protein and 10% squid (crumble #1 or #3, Rangen Feeds, Buhl, ID). Two continuous automatic feeders were utilized to deliver 25–50% of the dry feed with the remaining feed being hand delivered six times per day. Feed was offered in excess for the first 2 weeks, after which feeding rates were adjusted according to weekly growth rates and feed residues.

Table 2
Summary of shrimp production under various culture conditions

Species (date)	System	Stocked	No./m ³	Day ^a	Mean weight (g) ^b	Biomass		EFCE (%) ^c	Survival (%)
						kg ^c	kg/m ³ ^d		
<i>P. setiferus</i> (6/93)	Nursery 35-m ³	21 000	2100	28	0.18	3.6	0.36	85.1	96.9
		20 358	582	99/111	5.2/6.4	119.5	3.41	49.4	99.0
<i>P. setiferus</i> (8/93)	Nursery 25-m ³	50 000	5000	32	0.14	6.3	0.63	69.5	87.0
		43 482	1739	120	4.3	142.4	5.70	56.9	76.4
<i>P. vannamei</i> (6/94)	Nursery	60 000	6000	34	0.45	22.9	2.29	110.6	84.8
		25 450 ^f	1018	161	16.1	162.7	6.51	25.4	44.8 ^g
		25 450 ^f	1018	161	17.7	225.0	9.00	35.9	56.4 ^g
		5792	165	161	19.5	101.4	2.90	36.0	89.8
<i>P. vannamei</i> (6/95)	Nursery	83 000	8300	31	0.37	28.6	2.85	96.2	96.0
		79 724	3189	77	3.46	280.7	11.23	81.2	87.8
		64 970	902	172	12.7	644.5	8.95	24.3	78.3
<i>P. vannamei</i> (2/96)	Nursery	82 000	8200	21	0.16	12.3	1.22	94.1	92.4
		50 408	700	175	15.6	523	7.26	29.6	66.7

^a All shrimp were received as PL8-15. Day denotes the number of days from receipt of the population and indicates the culture day that the population was moved or harvested.

^b Mean weight of at least 30 individuals, towel dried and weighed individually.

^c Wet weight at harvest.

^d Kilograms of shrimp harvested per cubic meter of culture water.

^e Estimated feed conversion efficiency (EFCE) = biomass gain/total feed offered × 100.

^f At day 90 a portion of the shrimp (2896) having a mean weight of 8.6 g were transferred to the 35-m³ system.

^g Shrimp jumping out of the culture system was estimated to result in 11.8% mortality.

System maintenance such as siphoning of settled solids and the replacement of culture water was performed as needed and generally only occurred after 3 weeks of culture. A sub-sample of shrimp was collected on a weekly basis to estimate growth rates. Dissolved oxygen (DO), temperature and salinity were measured daily. Total ammonia-nitrogen, total nitrite-nitrogen and pH were measured 2–3 times per week using the methods described by Spotte (1979).

Prior to harvest, the culture water of the nursery system was lowered to visually inspect the shrimp and flush the system to stimulate molting. Harvesting was conducted by draining the system and netting the shrimp. Collected shrimp were weighed and transferred to the grow-out systems. Three sub-samples of shrimp (approximately 300 shrimp per sample) were collected during harvest, weighed as a group and the shrimp enumerated. The wet weight was then utilized to estimate final numbers in the population. Estimated feed conversion efficiency (EFCE) was calculated based on the biomass gain per unit of dry feed offered. Final weights, survival and EFCE were determined for each population.

Due to an outbreak of Taura syndrome in Texas during the 1995 season, the last two nursery trials with *P. vannamei* were conducted under quarantine conditions. Hence, no water was exchanged during the grow-out period. Siphoning of settled solids was minimized and all waste water was sterilized with chlorine and then neutralized with thiosulfate prior to discharge.

2.2.2. *Grow-out phase*

At the conclusion of the nursery phase each population was transferred to the appropriate grow-out system (Table 2). The first population of *P. setiferus* juveniles was transferred to the 35-m³ raceway and stocked at a density of 582 shrimp/m³. These shrimp were then partially harvested after a total of 99 days of culture with the remaining shrimp harvested at day 111. The second population was transferred to a 25-m³ raceway and stocked at a density of 1739 shrimp/m³ and maintained through 120 days of culture. The shrimp were initially fed a commercial shrimp feed (# 3 crumble) containing 45% protein and then switched to a 3/32-inch pellet containing 40% protein (Rangen Feeds Inc.) after 57 and 63 days of culture for the first and second populations, respectively. Feed was offered 6 times per day with feeding rates adjusted based on growth and feed residues remaining on the bottom of the culture tanks 1 h after feeding.

Daily system maintenance included feeding (2–6 times/day), washing the micro-particulate screens with fresh water (1 time/day), determination of water quality (DO, salinity and temperature) and the recording of collected data. Weekly maintenance included the determination and recording of water quality data (total ammonia-nitrogen, nitrite-nitrogen and pH), the addition of soda ash for pH adjustments and the siphoning of settled solids and exuviae from the system. Ozone (2–4 CFH) and oxygen (1–4 CFH) were added to the system at adequate levels to maintain oxygen levels near saturation.

The first population of *P. vannamei* post-larvae was maintained in the nursery system for 34 days under intensive stocking densities (6000/m³). After the nursery phase the population was split and stocked into two 25-m³ raceways with equiva-

lent configurations. After a total of 90 days of culture 2896 shrimp having a mean weight of 8.6 g were transferred from each of the 25-m³ raceways and stocked into a third raceway (35 m³) at a density of 165 shrimp/m³. All three raceways were harvested after a total of 161 days of culture. No water was exchanged from the system until day 82 at which time the micro-particulate removal system was initiated. System maintenance was as previously described.

The second population of *P. vannamei* was quarantined and evaluated for Taura syndrome prior to utilization. At the conclusion of the nursery phase the population was moved to a 25-m³ raceway and stocked at a density of 3189 shrimp/m³. The shrimp were maintained in this system for 36 days (total of 77 days of culture). System maintenance and feeding schedules were as previously described with the micro-particulate removal system operating throughout this phase of the culture period. The raceway was harvested by netting the shrimp. After weighing, the shrimp were transferred to the 72-m³ raceway. After 1 week approximately 5000 shrimp were harvested for other studies resulting in a density of 902 shrimp/m³ (64970 shrimp) for final growout.

System maintenance of the 72-m³ raceway was similar to that of the other systems with the following modifications. The 72-m³ system contained a primary settling chamber and clarifier. The primary settling chamber contained a 3-inch drain line running the length of the chamber, which could be intermittently opened for about 30 s to clear settled solids from the system. Additionally, the settling chamber, clarifier and culture chambers were vacuumed to remove settled solids. Floating solids, which accumulated in the clarifier, were removed by a skimming drain on an as-needed basis. At stocking, the raceway system was in the final stages of construction and the biological filters could not be conditioned. Consequently, during the first 2 weeks about 25% of the water in the system was exchanged on a daily basis. Upon activation of the biological filters, make-up water was exchanged at a rate of 6–8 l/min (12–16%/day) which was required to replace water used to clean the micro-screens.

The third population of *P. vannamei* was also quarantined and evaluated for Taura syndrome prior to utilization. At the conclusion of the nursery phase the population was moved to the 72 m³-raceway and stocked at a density of 700 shrimp/m³. System design, maintenance and feeding procedures were as previously described with the following modifications; (i) the micro-particulate system was bypassed allowing water to directly enter the settling chamber; and (ii) a drainage system was installed to allow all waste products and associated make-up water to be directed into an outside collection system. The collection system consisted of a primary settling chamber (0.8 m³) and secondary algae culture tank (1.6 m³). As the system filled water was returned from the algae tank to the culture chamber via a small submersible pump. These modifications allowed the system to run as a closed-loop system with minimal water exchange. Although hand feeding was also performed, four belt feeders were installed to provide continuous feed inputs.

2.3. Effluent waste production

To estimate waste production from the culture system, effluents from the micro-screen were passed through a settling chamber and the solids collected over several 24-h periods. To settle the solids, a small baffled sediment trap (48 × 38 × 15 cm) was utilized to collect settled solids leaving the micro-screen system. Solids were collected near the end of the first production run with *P. vannamei*. Samples of solids were then dried and analyzed for protein (total Kjeldahl-nitrogen) and ash utilizing methods described by Association of Official Analytical Chemists (1984) and for phosphorus content by the method of Fiske and Subbarow (1925).

3. Results and discussion

3.1. Nursery phase

Over a 6-year period 10 production runs with *P. vannamei* and three production runs with *P. setiferus* were successfully conducted utilizing the described systems. The presented data is typical of results for the production of both food and bait shrimp utilizing a variety of stocking strategies and system configurations. The nursery system has consistently produced high survival rates and efficient feed utilization (Table 2). The high EFCE values are probably the result of good feed management, high survival rates and recycling of nutrients through bacteria and possibly algae in the production system. This simple system has supported final biomass loads as high as 2.8 kg/m³ utilizing *P. vannamei* and 0.6 kg/m³ utilizing *P. setiferus* with consistent results. Potential problems seen in this system have been associated with ammonia removal and the maintenance of adequate oxygen levels in the culture water during the final week of production. High feeding rates, which are required to maintain acceptable growth rates of PLs, can lead to a build-up of organic waste products and bacterial loads in the system. If waste products are not removed or detoxified they can lead to deterioration of water quality. This is exemplified by high total ammonia-nitrogen (TAN) levels observed in the *P. vannamei* nursery runs conducted under quarantine conditions. In both runs only a minimal amount of solids removal and water replacement was conducted which resulted in increased levels of TAN during the final week of culture (Table 3). Water quality problems can be easily addressed by improving the filtration/aeration process or simple replacement of make-up water. Given the ability of PLs to utilize primary production as a nutrient source and our desire to maintain quarantine conditions, we have opted to keep the system relatively simple and allow a reasonable amount of nutrient build-up. With the exception of mortality associated with shipping of PLs, we have had no major mortalities or disease outbreaks during the nursery phase.

The production results observed in this nursery system are similar to those summarized by Samocha and Lawrence (1992) for intensive nursery systems under a variety of management conditions. The primary difference between these systems

Table 3
Summary of water quality parameters for the major phases of production

Species (date)	System	Temperature (°C)	Salinity (ppt)	Dissolved oxygen (mg/l)	Total ammonia-N (mg/l)	Nitrite-N (mg/l)	pH
<i>P. setiferus</i> (6/93)	Nursery 35-m ³	27.7 (2.48) ^a	28.3 (2.48)	5.5 (0.54)	0.17 (0.14)	0.17 (0.23)	7.7 (0.20)
		28.1 (1.14)	31.0 (2.28)	6.5 (0.98)	0.30 (0.23)	0.74 (0.54)	7.5 (0.21)
<i>P. setiferus</i> (8/93)	Nursery 25-m ³	27.2 (1.60)	33.2 (2.74)	5.3 (0.51)	0.32 (0.19)	0.30 (0.18)	7.5 (0.22)
		24.7 (2.22)	29.2 (2.27)	7.0 (0.68)	0.18 (0.17)	0.12 (0.05)	7.5 (0.26)
<i>P. vannamei</i> (6/94)	Nursery 25-m ³	28.0 (0.80)	22.6 (6.85)	6.0 (0.90)	0.38 (0.27)	0.31 (0.30)	7.6 (0.28)
		27.5 (1.78)	31.8 (2.62)	6.8 (1.28)	0.41 (0.15)	0.43 (0.58)	7.4 (0.14)
		27.7 (1.74)	31.6 (3.05)	7.0 (1.53)	0.37 (0.15)	0.60 (0.70)	7.4 (0.12)
		26.1 (1.53)	29.3 (3.33)	6.2 (1.07)	0.36 (0.14)	0.30 (0.19)	7.6 (0.17)
<i>P. vannamei</i> (6/95)	Nursery 25-m ³	29.5 (1.23)	29.5 (2.17)	6.1 (0.51)	0.76 (0.94)	0.31 (0.28)	7.49 (0.27)
		29.5 (0.62)	33.1 (1.33)	6.7 (1.68)	0.66 (1.05)	0.98 (0.41)	7.40 (0.25)
		27.5 (1.74)	28.0 (2.77)	6.4 (1.07)	0.54 (0.32)	0.79 (0.27)	7.51 (0.15)
<i>P. vannamei</i> (2/96)	Nursery 72-m ³	24.0 (2.32)	31.3 (2.94)	6.4 (0.63)	1.16 (0.91)	0.51 (0.44)	7.6 (0.09)
		28.9 (3.65)	23.9 (4.96)	5.6 (1.15)	0.50 (0.30)	1.48 (1.01)	7.5 (0.23)

^a Numbers in brackets indicate standard deviation.

is our utilization of a biological filter and recirculating techniques to maintain water quality parameters and minimize water usage. Based on our observed results, this simple nursery system is reliable, relatively maintenance free and suitable for the quarantining of PLs.

3.2. *Production of bait shrimp*

At the conclusion of the nursery phase, the juvenile shrimp were transferred to the grow-out systems. The production of bait sized *P. setiferus* was completed within 100–120 days of culture. Survival rates ranged from 99% for shrimp maintained at low density (582 shrimp/m²) to 76% for shrimp maintained at the higher density (1739 shrimp/m²). The reduction in survival was probably, due in part, to the high stocking density. This trend is consistent with results observed by Williams et al. (1996), who reported an inverse relationship between stocking density and survival of *P. setiferus*. Although increased density reduced survival, the final biomass production per cubic meter of culture space was considerably higher (5.7 kg vs. 3.4 kg) in the high density system. Given the similar EFCE values observed, it may be cost effective to sacrifice survival rates for final biomass production. Densities above 1739/m³ have not been evaluated with *P. setiferus* but higher densities (3189 shrimp/m³) have been evaluated with *P. vannamei*. Although these shrimp were harvested at a slightly smaller size than the bait shrimp, acceptable survival rates, good EFCE values, and high biomass loading (11.23 kg/m³) were obtained. These results may indicate that *P. setiferus* could be raised at higher densities targeting a final biomass loading of 10 kg/m³.

Upon harvest, the shrimp were transferred to a local bait stand for distribution to the public. Mortality after transport and during holding at the bait stand was negligible. Shrimp from these fall/winter harvests were readily accepted by the local dealer and the fishing public. The live bait shrimp market would appear to be a potential outlet for shrimp produced in intensive systems. Although this market is present year-round, the price varies with season, availability of wild shrimp and demand from sport's fishermen. Locally, the wholesale price varies from \$3 to \$4/lb depending on fishing demand and availability of shrimp from the wild.

3.3. *Production of food shrimp*

The final three production runs describe results with *P. vannamei* targeting a 16-g food shrimp. The production runs were selected to demonstrate various stocking strategies that may be utilized and the range of growth rates observed. In the first production run (initiated June 1994) juveniles were stocked at high density into two identically configured raceways. After 90 days of culture 25 kg of shrimp (8.6 g mean wt) were removed from each raceway and stocked into a third system at low density (165 shrimp/m³). All the shrimp were harvested after a total of 161 days of culture. This production strategy allowed an estimate of the growth potential in a two phase intensive system as compared to a three phase production system utilizing low density stocking rates for final growout. Survival and final weights of

the shrimp in the high density system were typical of production runs at this density. The higher survival rate observed at the low density was probably due to a combination of factors which include a shorter holding period, density dependant survival, and reduced mortality due to jumping out of the raceway. Williams et al. (1996) demonstrated a negative correlation between stocking density and survival of *P. vannamei* which corresponds to our observations under production conditions. We have also found that under intensive conditions the shrimp tend to be startled, thus setting off an incidence of jumping shrimp. Despite the fact that the raceway is covered with a net, we estimated that a mortality of 11.8% was attributable to shrimp escaping through the net. In addition to better survival rates (89.8% vs. 44.8 or 56.4%) shrimp transferred to the low density system were larger at harvest (19.5 vs. 16.1 or 17.7 g). The increased size may warrant better prices for the shrimp; however, this was only achieved by sacrificing final biomass loads.

In the second production run, a three phase system was evaluated that would allow a more optimal loading of the culture systems. After the initial nursery phase, the shrimp were stocked into a juvenile grow-out system at high density (3189/m³) for 36 days. At the conclusion of the juvenile growout (total of 77 days of culture), the shrimp were moved and stocked into the final grow-out system at a density of 902 shrimp/m³. Survival in both phases of growout was good (87.8 and 78.3%) resulting in a combined survival rate of 68.6%, which is comparable to that observed in the other two production runs with *P. vannamei*. Despite good survival, the shrimp harvested in this production run were smaller than our target of 16 g. This reduction in final weight may have been associated with poor water quality conditions that occurred during this production run. Poor water quality conditions occurred in the final week of the nursery phase and the initial weeks of the final grow-out phase. Both problems were the result of filter maintenance and system modifications that were carried out during the production run. Although final weights were below our target level, final biomass loading of each stage of the production was very good.

The utilization of phased production systems, such as the three phase system previously described, has a variety of advantages when multiple crops are desired. Advantages include the opportunity to evaluate stock inventory (biomass and survival) as well as a more efficient utilization of space and nutrient loading of the culture system. The production of staggered crops also allows for a more continuous supply of shrimp for sale and reduces peak demands for post-larvae.

The final production run with *P. vannamei* was conducted under quarantine conditions during the first 2 months of culture. To simplify quarantine procedures, juveniles were stocked directly into the 72-m³ grow-out system, the micro-screen system bypassed, and suspended solids removed by settling. Additionally, waste products associated with system cleaning, such as settled solids as well as floating bacterial mats, were drained into an outside collection basin for bacterial degradation. This waste water was then pumped directly back into the raceway without further treatment. Although little water was exchanged during this production cycle, survival and growth rates were similar to those observed in previous production runs.

In general PL and juvenile growth as well as EFCE have been very good. The growth rates observed in these production runs are below the maximum growth rates of about 2 g/week which can be obtained in outdoor production systems under optimal conditions. However, they are similar to the 0.94 g/week reported by Sandifer et al. (1991) for super intensive pond production systems. Additionally, survival rates are similar to rates commonly seen in commercial pond production systems as summarized by Hopkins and Villalón (1992). As exemplified by Williams et al. (1996) the reduced growth rates and survival would appear to be partially due to crowding but may also be due to other factors such as deficiencies in the feed.

The EFCE rates in the juvenile grow-out were comparable to those obtained with *P. japonicus* juveniles and those reported by Samocha and Lawrence (1992) for nursery production of *P. vannamei* juveniles. However, EFCE were generally lower for the grow-out phase of production. The poor EFCE during growout is probably due to the difficulty in predicting feed consumption and survival rates in combination with our desire to ensure that feed availability is not a limiting factor. Feed conversion was highest during the short juvenile growout utilized in the second production run with *P. vannamei*. The high EFCE values observed during this stage were presumably obtained due to the relative ease of feed management over short periods of time (36 days) during which mortality was relatively low. In our latest production run with *P. vannamei*, which included overwintering, an EFCE of 50.4% was obtained by reducing feed inputs during the grow-out phase. Even in the absence of natural productivity and with feeding rates in excess, EFCE of 25–30% observed in our production runs are similar to low values seen in pond production systems as summarized by Hopkins and Villalón (1992), and under intensive pond production conditions reported by Sandifer et al. (1991) and Wyban and Sweeney (1989).

Since feed availability does not appear to be a problem, future management strategies should attempt to optimize feed inputs and feed formulations for the final grow-out systems. The optimization of feeding rates would not only reduce feed costs but would also positively influence water quality. Although feed utilization may be improved, without access to natural forage, feed costs and consequently production costs, will always be higher for indoor production systems.

One potential advantage of semi-closed systems is the ease of removing solid waste products and consequently the control of effluent pollutants. To estimate waste production captured by the micro-screen system, the discharge from the micro-screens were settled and quantified. Waste captured in the sediment trap accounted for 22–30% (on a dry weight basis) of the feed input. Proximate analysis of the waste was as follows: total nitrogen, 1.8 g/100 g dry weight; ash, 83.2 g/100 g dry weight; phosphorus, 104 µg P/g dry weight. Although these solids can be left in the system for degradation, removal from the system reduces the nutrient loading and consequently enhances system performance.

Under normal operation, we allow the waste stream to leave the culture system for external treatment or discharge, resulting in a slow water exchange (10–15%/day). This exchange can be significantly reduced by utilizing the culture water to operate the spray bar which washes the micro-screen filter. Additional savings in

water usage can be obtained by settling solids from the waste stream and returning the water to the culture system. The settled solids can then be discharged on a daily basis. Both methods have been utilized with the later resulting in very low (60 l/day or 0.2%/day) levels of water usage. Another option for reduction of water use is to eliminate the micro-screen system and utilize settling to remove suspended solids.

In the final production run with *P. vannamei*, the 72-m³ raceway was run as a closed-loop recirculating system utilizing settling chambers to remove suspended solids and an external treatment system to process solid waste. This system allowed for the external treatment of the concentrated waste products and reuse of the waste water. One added benefit of this system was a continuous production of algae and live foods such as rotifers that were utilized as supplemental feed sources for larval fish in other production systems.

The primary diseases observed under the described production conditions have been generally associated with poor water quality and/or stress due to crowding. Based on histological examinations of juveniles and sub-adult shrimp, melanization and bacterial fouling of the gills, as well as external melanization associated with *Vibrio* and *Mycobacterium* sp. have been noted. The melanized lesions of the exoskeleton resulting in black spots can reduce the value of shrimp. Similar spotting is found in both wild and cultured shrimp and under normal culture conditions, only low levels of spotting occur. For the described production runs, commercially produced high health PLs were utilized; viral infections, such as Taura syndrome, which resulted in poor survival in pond based production systems in Texas during the 1995 and 1996 production seasons, have not been observed in our production systems to date. These results are encouraging and may indicate that this type of system is less likely to suffer from disease problems encountered in pond based systems.

4. Conclusions

Based on a history of consistent production, it is clear that shrimp can be produced under intensive conditions utilizing relatively simple technologies and commercially available feeds. The utilization of a nursery system produced consistent results, increased the accuracy of stocking and facilitated the holding of shrimp under quarantine conditions. Both bait and food shrimp have been produced with final biomass loads as high as 10 kg/m³ utilizing 100–120-day and 160–175-day production cycles, respectively.

Results of the multi-phase growout are most promising and indicate that this may be a suitable mechanism to optimize biomass loading and hence system efficiency. Consequently, a multi-phase production system similar to that used with fish is recommended if continuous production is desired. Although, the three phase system was efficient, it would appear that breaking the production into a 5-week quarantine followed by three 6-week grow-out periods could further optimize loading of the culture systems. Such a system would allow for harvesting and the initiation of a new population every 6 weeks facilitating the development of a

continuous supply for marketing. Although the economic viability of recirculating production systems for bait or food shrimp have yet to be proven, the consistent results, low water usage, and ease of waste management are encouraging and warrant further economic and marketing evaluations.

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