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A commercial-scale, in-pond raceway system for Ictalurid catfish production

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ARTICLE INFO

Article history: Received 16 December 2010 Accepted 23 March 2011

Keywords: In-pond raceway system Catfish production Water recirculation

ABSTRACT

A commercial-scale, in-pond raceway system was constructed in 2007 on a commercial catfish fish farm in west Alabama. The in-pond raceway system was installed in a 2.43-ha earthen pond with an average depth of 1.67 m. A slow-rotating paddlewheel (1.17 revolutions per minute) installed in each raceway produced a water velocity of 0.026 m/s and a water flow rate of 9.3 m³/min. This flow rate was equivalent to an average water exchange for each raceway every 4.9 min (\approx 12×/h). Each raceway was originally stocked with 12,000–30,000 advanced channel catfish (*Ictalurus punctatus*) and hybrid catfish (*I. punctatus* × *Ictalurus furcatus*) fingerlings weighing between 59.1 and 418.2 g to simulate a staggered stocking and harvest production schedule. During the 2008 production season, mean survival was 83.7% across all raceways. Growth rates ranged from 1.1 to 1.8 g/fish/day for channel catfish and from 1.6 to 2.2 g/fish/day for hybrid catfish. The average feed conversion ratio (FCR) for channel catfish and hybrid catfish was 1.74 and 1.36, respectively (range from 1.16 to 2.11) and 49,913 kg (20,540 kg/ha) of catfish were harvested. An additional 6365 kg (2619 kg/ha) of tilapia and paddlefish were harvested from the pond as co-cultured species. The results indicated a high potential for efficient production of catfish with other co-cultured species compared to traditional catfish culture practices in ponds. Design and engineering modifications need to be addressed in the future to improve the in-pond raceway system.

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1. Introduction

The largest segment of United States (U.S.) aquaculture is the production of *Ictalurid* catfish. In 2008, 232,000 tonnes of food size channel catfish, *Ictalurus punctatus*, were produced with an estimated value of \$410 million (USDA, 2009). About 92% of total U.S. sales were produced in Mississippi, Alabama, Arkansas, and Texas. Additionally in 2008, 1617 catfish operations existed in the U.S. with a total of 66,005-water ha (USDA, 2009). As of January 2009, only 1306 of the original farms still operated on a total of 59,450-water ha with a reduction of 19.2% in farms and 9.9% in area.

Channel catfish farming also is the most important aquaculture sector in Alabama. In 2008, there were 252 farms in Alabama that utilized 8984-water ha and produced 59,693 tonnes of catfish (USDA, 2009). The economic impact on Alabama is substantial with approximately 3000 Alabamians engaged directly in the catfish industry (Chappell and Crews, 2006).

Catfish are primarily cultured in embankment ponds or watershed ponds and are harvested by seining. Despite being relatively land and labor intensive, pond production can be efficient and profitable if production levels are increased through techniques that maintain adequate water quality (Boyd and Tucker, 1998). The traditional pond system typically produces 4500–5500 kg/ha of catfish with a maximum of 7000 kg/ha (Brune, 1991; USDA, 2006). However, today, many farms in Alabama produce more than 10,000 kg/ha, and the amount of aeration provided is not adequate to consistently maintain minimum dissolved oxygen (DO) concentrations above 3 mg/L (Boyd and Hanson, 2010). The need for improved management is reflected in the high feed conversion ratio (FCR). Based on USDA/NASS data on food-size catfish production and grow-out feed deliveries to farms in the U.S. between 2005 and 2009, FCR averaged 2.67. An FCR of 1.6–1.8 is considered acceptable in well-managed ponds (Boyd and Tucker, 1998).

Catfish farming must become more efficient to remain profitable and sustainable. Thus, in addition to the urgency in improving traditional pond production methodology, there is a demand for more efficient production techniques for raising channel catfish. Early attempts at intensifying culture practices for warm water fish involved raceway, tank and cage culture (Andrews et al., 1971; Hill et al., 1974; Schmittou, 1969). However, farmers already have ponds and Auburn University began research on floating, in-pond raceways in the late 1990s in an attempt to develop a new methodology that could be installed in existing ponds (Masser, 2004). The basic floating, in-pond raceway consisted of a floating raceway stocked with catfish fingerlings. Airlift pumps circulated pond water through the culture unit and a waste removal system was

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utilized to capture solid fish waste from the end of the raceways (Hawcroft, 1994; Bernardez, 1995; Wilcox, 1998). Although the original system was successful in research settings, it had several disadvantages including uneven water flow throughout the raceways and low efficiency of solid waste removal. After continued research for several years, the problem with uneven water flow was corrected by building the airlifts identical to each other, attaching each airlift to the same air-manifold, and installing a restriction orifice at the attachment of the air-manifold to the air-line (Masser and Lazur, 1997). Moreover, survival was initially low because of disease outbreaks, but improved as research progressed. Consequently, several more alterations have been made in system design and operational procedures to increase the uniformity and volume of water flow and maximize the opportunity for biomass loading. However, the use of in-pond raceways has not been adopted by producers.

More recent studies demonstrated new aquaculture production practices that utilize high rate photosynthetic systems. They are the partitioned aquaculture system developed at Clemson University (Brune et al., 2004), and the split-pond system that has been constructed at the Delta Research and Extension Center at Stoneville, MS (Tucker and Kingsburg, 2009). These systems combine a number of biological, chemical, and physical intensification elements into a single, integrated system that may prove more controllable and efficient than traditional pond culture.

The present study describes a modification of the in-pond raceway system in which the raceways are fixed rather than floating. The efficiency of this system in producing catfish in the raceways and co-cultured species in the surrounding pond also is discussed.

2. Materials and methods

2.1. System layout

This study was conducted on a 174-water ha commercial catfish farm in Browns, AL. The in-pond raceway system was installed in a 2.43-ha, traditional, earthen pond supplied by both well water and watershed runoff. The system consisted of six individual raceways that share common walls attached to a permanent concrete

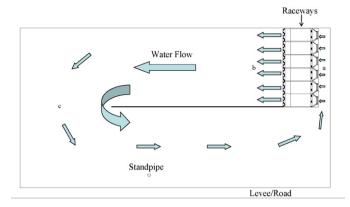


Fig. 1. A schematic layout of the in-pond raceway system showing the direction of water flow throughout the pond and the raceways including water inflow (a), water outflow (b), and the opposite end of the pond (c).

foundation (30.48 m \times 13.72 m wide \times 1.42 m deep) Each raceway $(13.71 \,\mathrm{m} \times 4.88 \,\mathrm{m} \times 1.22 \,\mathrm{m})$ consisted of three separate components: slow rotating paddle wheel area $(3.11 \text{ m} \times 4.88 \text{ m} \times 1.22 \text{ m})$; fish culture area $(7.71 \,\mathrm{m} \times 4.88 \,\mathrm{m} \times 1.22 \,\mathrm{m})$; and waste settling area $(2.89 \,\mathrm{m} \times 4.88 \,\mathrm{m} \times 1.22 \,\mathrm{m})$. The walls were constructed of standard cinder blocks $(0.46 \, \text{m} \times 0.20 \, \text{m} \times 0.20 \, \text{m})$ filled with concrete and supported with 1.3 cm reinforcing bar. The fish were confined in the culture unit by an end partition barrier that spanned the width of each raceway unit. Each partition had a frame constructed of 3.8 cm² aluminum tubing (wall thickness of 0.32 cm). PVC-coated, steel-mesh wire (0.15 cm diameter) was attached to the frame by means of 0.6-cm, flat-bar aluminum, 10.0-mm, zinc-plated, self-taping screws, and 5.0-mm aluminum rivets. Three different mesh sizes were utilized throughout the experiment (12.7 mm \times 25.4 mm, 25.4 mm \times 25.4 mm, and $25.4 \, \text{mm} \times 50.8 \, \text{mm}$) depending on the initial size of the stocked fish. Two walkways (30.48 m long \times 0.76 m wide) were utilized to access individual raceways and the system components. The first walkway is located directly above the water inflow to the fish culture unit and the second 7.71 m downstream (Figs. 1 and 2).

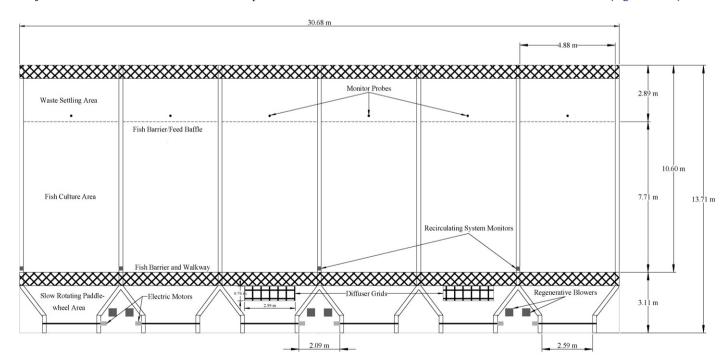


Fig. 2. A schematic layout of the complete in-pond raceway system.



Fig. 3. The in-pond raceway system located in Browns, AL.

Each paddlewheel was constructed of six pieces of plywood $(2.44 \, \text{m long} \times 1.22 \, \text{m wide} \times 2.00 \, \text{cm thick})$ which are evenly distributed around a 5.87-cm diameter, central shaft. The plywood was mounted on a steel frame attached to the central shaft with angle iron (5.08 cm at 90°) and 6.4-mm, carriage-bolts. The paddlewheel had an overall diameter of 2.50 m. Each individual paddlewheel was powered by a 0.37-kW, 3-phase, electric motor (Blador, Fort Smith, AZ) that rotated at 1750 rpm. The motor was attached to a gear box (Iron Man, Cleveland, OH) that reduced the electric motor shaft speed by a factor of 7.5:1. The gear box was attached to a speed reducer (SHIMPO CIRCULATE, Itaska, IL) to further reduce the rotational speed by a factor of 233:1. An 11-tooth sprocket was attached to the output end of the speed reducer, and a chain connected the sprocket of the speed reducer to the 33-tooth sprocket of the central shaft of the paddlewheel. The combination of the electric motor, gear box, speed reducer, and sprockets with chain produced a paddlewheel rotational speed of 1.17 rpm at 70 Hz. The paddlewheel allowed a constant distribution of water flow through the culture unit to continually supply oxygenated water to the fish and to flush out waste.

Water flow through a random raceway was measured before fish were stocked using a flow meter (Marsh-McBirney, Inc., Model-2000, Frederick, MD). Five points were selected at equal distances across the water inflow and water outflow sections, and five measurements were made at 20% and 80% of water depth for a total of 100 measurements (Bankston and Baker, 1995). Average velocity was multiplied by the width of the raceway and the height of the water column to determine discharge, and water exchange rate was calculated. Water flowed from raceways into the north side of the pond, moved counterclockwise to the south side of the pond, and returned to the inflow side of the raceways; a baffle attached to the outside wall of raceway 6 extends 122 m into the pond and prevents short circuiting of return flow to the raceways (Fig. 3).

Aeration for each raceway was supplied by a 1.12-kW regenerative blower (Sweetwater, Aquatic Eco-Systems, Inc., Apopka, FL) capable of delivering 2.4–2.6 m³/min of air directly into the water column via a diffuser grid airlift located between the paddlewheel and the first partition barrier in the slow rotating paddlewheel area (Fig. 2). The regenerative blowers were operated approximately 4 h per day throughout the study. The diffuser grid (2.59 m long × 0.76 m wide) was constructed of schedule 80 PVC (5.08-cm diameter), barbed fittings (1.27-cm diameter), and 2.54-cm diameter diffuser tubing (Colorite Plastics Company, Ridgefield, NJ). Barbed fittings were plumbed into the PVC frame of the grid

every 6.65 cm. The diffuser tubing (a total of 52.89 m per grid) was attached to the barbed fittings to allow even distribution of air flow throughout the grid. Emergency aeration was applied by a 7.5-kW paddlewheel aerator for an average of 4 h per day. Both the airlift aeration device and paddlewheel aerator were tested for standard oxygen transfer rate and standard aeration efficiency at Auburn University, Auburn, AL (Boyd, 1998).

The feed delivery system consisted of three main components: a 10-tonne bulk feed bin; 7.62-cm diameter feed auger; and six 80-kg capacity feed hoppers. The bulk feed bin was plumbed into a delivery auger that extends to the exterior wall of the last raceway. The auger was powered by an electric motor (BROCK Grain Systems, Milford, IN), and had a manual/automatic switch with sensor to allow the operator to continually monitor and maintain desired feed delivery levels throughout the system. Each raceway had its own individual feed hopper (Sweeney Enterprises Inc., Boerne, TX) to which feed was delivered from the main auger line. The hoppers were located at the water inflow and in the center of each raceway. Each feed hopper was powered by a 12-V electric motor (Sweeney Enterprises Inc., Boerne, TX) wired into a main control box with switches for controlling feed delivery to each raceway.

The electrical service monitoring system that was installed consisted of three main components: an autodialer (Sensaphone Model 400, Aston, PA); recirculating system monitor (YSI 5200, Yellow Springs, OH); and computer aided management program (YSI Aquamanager, Yellow Springs, OH). The autodialer was programmed to call the manager during emergency conditions such as a power failure or low DO concentration.

Recirculating system monitors (YSI, Yellow Springs, OH) were installed to monitor both DO and temperature in the outflow water of each raceway. A monitor probe was also placed in the water inflow channel. Monitoring allowed the computer-aided management program to oversee measurements for the entire system, collect data, and control aerator operation based on DO concentration.

2.2. Culture conditions

Fingerlings of channel catfish (*I. punctatus*) and hybrid catfish (*I. punctatus* × *Ictalurus furcatus*) were obtained throughout the experiment from commercial suppliers (Eagle Aquaculture, Indianola, MS and Aquacenter, Leland, MS). A portion of the raceways contained fish before the start of the study, so an initial inventory was conducted. Existing fish were crowded, harvested, weighed, sampled, and restocked into designated raceways on March 13, 2008. Upon arrival on March 28, 2008, new fingerlings were sampled to examine for disease and to measure initial weight. Fingerlings were acclimated (5 °C/h) to culture conditions using partial water exchanges to equalize environmental conditions. Once the initial inventory and fingerling acclimation were complete, fish were stocked into the raceways at densities ranging from 17.7 to 118.3 kg/m³ (Table 1).

The grow-out phase was conducted over 89–250 days depending on size of fish initially stocked and optimal harvest size required by the processing plant. The catfish were offered a 32% protein, floating commercial feed (Alabama Feed Mill, Uniontown, AL) 2–4 times per day based on biomass, water temperature and fish size. For example, catfish fingerlings are usually fed 6.0% of their total body weight per day at water temperatures between 26 and 30 °C as opposed to food fish which are usually fed 3.0% of their total body weight per day at that same water temperature. The maximum total daily feed ration for a raceway that had a total biomass of 3000 kg of fingerlings and an average water temperature of 27 °C would be 180 kg (3000 kg fish \times 6.0% body weight/day).

Temperature, DO concentration, pH, and salinity were measured in situ with portable meters at dawn and dusk daily in the water

Table 1Channel catfish and hybrid catfish stocking and harvest densities for the in-pond raceway system in Browns, AL.

Fish species and rearing location	Stocking de	nsity	Harvest density		
	(fish/m ⁻³)	(kg/m³)	(fish/m ⁻³)	(kg/m ³)	
Channel catfish					
Raceway 1b	300	17.7	198	54.9	
Raceway 2	256	45.4	244	143.9	
Raceway 5	655	92.3	503	199.0	
Hybrid catfish					
Raceway 1a	253	105.7	247	158.6	
Raceway 3 (split into 3 and 4) ^a	186	117.0	171	141.5	
Raceway 4	261	118.3	242	176.1	
Raceway 6	556	34.8	459	214.7	

^a Raceway 3 reached maximum density and the decision was made to partial harvest approximately 50% of the biomass and stock into the neighboring raceway #4. Total weight of raceway 4 was known at the time of harvest, but estimations from fish samples had to be calculated for the remaining fish in raceway 3.

inflow channel and in the water outflow of the raceways. Water samples were collected weekly and analyzed for total ammonia nitrogen, nitrite nitrogen alkalinity, and chloride (Clesceri et al., 1998). Additionally, water samples were collected weekly at three points; water inflow, water outflow, and at the opposite end of the pond and analyzed for total ammonia nitrogen and nitrite nitrogen, while DO concentration and pH were measured daily at two points; water inflow and water outflow (Fig. 1).

Fish were stocked in the pond outside of the raceways to improve water quality by feeding on suspended solids from the raceways and plankton resulting from nutrients from the raceways and for the co-production of marketable fish. Paddlefish (*Polyodon spathula*) with an average individual weight of 328 g were obtained from Kentucky State University, Frankfort, KY, and stocked at a rate of 288 per hectare. Tilapia (*Oreochromis niloticus*) brood fish with an average weight of 232 g (Dean Wilson Farms, Browns, AL) were sexed and stocked at a rate of 12 breeding pairs per hectare. In addition, fathead minnows (*Pimephales promelas*) were stocked at a rate of 11.2 kg/ha (Clary Seining, Greensboro, AL) to reduce the chance of proliferative gill disease as described by Burtle (2000) while redear sunfish (*Lepomis microlophus*) were stocked at a rate of 37.2 kg/ha (Clary Seining, Greensboro, AL) to assist with the management of gastropods or specifically the ramshorn snail (Terhune et al., 2003).

Throughout the study fish were monitored for any signs of disease. Analysis of morbid fish was conducted by the disease diagnostic laboratory at the Alabama Fish Farming Center in Greensboro, AL. All recommendations, such as the use of potassium permanganate, were followed to treat any parasites found. Potassium permanganate baths (3.0–5.0 ppm), to control external parasites, were used when mortalities occured in the raceways. This type of treatment was commonly practiced at Auburn University (Hawcroft, 1994; Bernardez, 1995; Wilcox, 1998). The system allows for ease of advanced treatment as compared to treatment of fish in traditional ponds. The fish can be observed for diseases and treated periodically without having to treat the entire pond or water body. This is not only more economical, but it saves time.

System maintenance was conducted according to the following schedule: data collection (daily); cleaning probe membranes (daily); mortality check and carcass removal (daily); feed delivery system cleaning and calibration (weekly); calibration of DO probes (biweekly); chemical treatment of fish (weekly–monthly depending on water temperature); lubrication of sprockets and chains (monthly); regenerative blower filter cleaning (bi–monthly); were carried out on a regular basis. The estimated biomass in each raceway was adjusted daily by subtracting mortalities from the number of fish stocked then multiplying that value by the individual average fish weight. A weighted average from sample point A (i.e., day 1) to sample point B (i.e., day 30) was used to determine growth

over time. Catfish were sampled monthly to determine average size and total biomass in each raceway. The fish were crowded and dip nets were used to remove a sample of at least 100 fish from each raceway. Fish were weighed and counted to determine individual average weight. Average weight (nearest 1.0 g) was calculated for each sub-group by dividing the sample weight by the total number of fish in the sample. Individual length and weight measurements were taken on approximately 75 fish from each raceway and used to determine average total length and size distribution for each sub-group.

Total production (harvest weight – stocking weight) was calculated for each cohort of fish as total weight gain. Feed conversion ratios for each cohort of fish were calculated by dividing the amount of feed consumed per amount of weight gained. Average, daily, weight gain per fish was calculated by dividing the total production weight of each cohort of fish by the number of days in the culture period and dividing that value by the total number of fish harvested. Fish were harvested on June 17, October 07, November 3, 11, and 18, 2008 for raceways 1a, 5, 2 and 3, 4, and 1b and 6, respectively. At harvest, the fish were crowded in the raceway and a boom truck equipped with a hoist net was used to weigh and load the fish into hauling tanks for transport to the processing plant. Catfish were harvested throughout the study as they reached a marketable size while paddlefish and tilapia were clean harvested by seining at the end of the study.

3. Results and discussion

The average water velocity in raceways was 0.026 m/s $(0.15 \,\mathrm{m}^3/\mathrm{s})$ which equates to a water flow of 9.3 $\mathrm{m}^3/\mathrm{min}$. This flow rate resulted in one water exchange every 4.9 min or \approx 12 times per hour (45.9 m³ tank volume/9.3 m³/min). Brune et al. (2003) observed water exchange rates ranging from 0.226 to 0.988 times per hour within individual culture units of the partitioned aquaculture system, while Hawcroft (1994) reported water exchange rates as frequent as once every 3.8 min, Bernardez (1995) once every 3.2 min, Martin (1997) once every 6.4 min, and Wilcox (1998) once every 6.2 min in an in-pond, floating raceway. High flow rate and water exchange are beneficial in maintaining adequate DO concentration at high fish densities and avoiding fish stress, especially at heavy feed rates during the warmer part of the production season (Boyd and Tucker, 1998). Soderberg (1995) recommended a minimal water velocity of approximately 0.033 m/s to eliminate solid waste settling at the rear of raceways. The six raceways of the inpond raceway system of the present study had a combined water flow of $55.7\,\mathrm{m}^3/\mathrm{min}$. Thus, the entire water volume in the pond theoretically flowed through the raceways every 12.1 h [(40,594 m³) pond volume/55.7 m^3/min)/60 min/h].

The recommended operating air flow rate from the manufacture of the diffuser tubing was approximately $0.047\,\mathrm{m}^3/\mathrm{min/m}$ length of hose. A standard pressure loss from the diffuser tubing of 2.98 kPa plus the additional pressure loss of $10.43\,\mathrm{kPa}$ from the diffuser water depth $(1.07\,\mathrm{m})$ yielded a total pressure loss of $13.41\,\mathrm{kPa}$. The standard oxygen transfer rate and standard aeration efficiency were determined to be $1.88\,\mathrm{and}\,12.96\,\mathrm{kg}\,\mathrm{O}_2/\mathrm{h}$ and $1.26\,\mathrm{and}\,2.87\,\mathrm{kg}\,\mathrm{O}_2/\mathrm{kW}\,\mathrm{h}$ for the diffuser aeration device and paddlewheel aerator, respectively.

The feed delivery system was inefficient at delivering feed to individual raceways, so a new design was adopted. The main problem with the initial delivery system was that the feed delivery lines were not sealed, and rain water flowed in to contaminate the feed after a rainfall event. This was corrected by re-plumbing the delivery lines and sealing them with silicon.

There initially was an uneven distribution of feed per raceway because feed fines accumulated at the funnel section of the hop-

Table 2Water quality variables measured in pond water samples collected from an in-pond raceway system (IPRS) in Browns, AL, as compared to optimum and tolerated levels for growth of channel catfish. Values of the IPRS represent the mean and standard deviation (SD).

Water quality variable	IPRS			Optimal level*	Tolerated level*	
	Min	Max	Mean ± SD			
Dissolved oxygen (mg/L)	0.98	19.83	6.38 ± 3.62	5–15	2.00	
Temperature (°C)	12.30	33.60	25.15 ± 5.12	27-29	0-40	
pH	6.99	9.33	7.74 ± 0.48	6-9	5-10	
TAN (mg/L)	0.23	4.75	1.45 ± 1.15	0 as un-ionized ammonia	<0.2 as N	
Nitrite-N (mg/L)	0.00	0.84	0.17 ± 0.19	0 as nitrite	Depends on chloride concentration	
Total alkalinity (mg/L)	117.70	187.20	164.60 ± 16.40	20-400	<1 to >400	
Total hardness (mg/L)	128.00	152.20	140.10 ± 8.60	20-400	<1 to >400	
Chloride (mg/L)	598.00	933.00	705.30 ± 75.60	_	-	
Salinity (g/L)	1.00	1.40	1.24 ± 0.12	0.5-3.0	<0.1-8.0	

^{*} Tucker and Robinson (1990).

per and water splashed by the feeding action of the fish created a paste that clogged the delivery funnel of the feed hopper and restricted feed delivery. This problem was corrected by cleaning and calibrating the feed hoppers on a weekly basis. A 20-L bucket was attached to the bottom of each hopper, power was applied to the feed broadcaster, and the amount of time was recorded for each feeding event. After weighing the amount of feed from each hopper in a given amount of time, a calibration factor was calculated for each feed hopper.

Water quality variables were within acceptable limits for catfish production throughout the experiment (Table 2). There were few instances when DO concentration fell below 3 mg/L, and fish were thought to have suffered little stress from water quality impairment from high total ammonia nitrogen (TAN) or nitrite nitrogen (Nitrite-N) concentrations. The elevated total alkalinity and total hardness were likely related to the water supply and pond bottom. The main water supply consisted of high concentrations of alkalinity and hardness and the pond bottom was mainly calcareous clay based limestone. Prior to the study additions of sodium chloride were added to the pond to improve osmoregulation capabilities of the fish and to prevent nitrite toxicosis or methaemoglobinaemia, commonly known as "brown blood disease". The combination of elevated total alkalinity, total hardness, and chloride concentrations was thought to have been beneficial for fish production and equated to a more balanced and stress-free rearing environment. This system demonstrated a high buffering capacity against diurnal fluxes in DO and pH which was more than likely associated with the use of mechanical aeration and elevated total alkalinity (Boyd and Tucker, 1998). Water inflow had a higher concentration of DO and pH as compared to the water outflow (Table 3). TAN and Nitrite-N were lower in concentration in the water inflow while water outflow was higher in concentration which would be expected due to fish respiration and metabolite production. Concentrations of TAN and Nitrite-N were lowest at the water inflow point indicating nitrification.

A total fish loading rate of $888 \, \text{kg fish/m}^3/\text{min}$ was calculated by dividing the mean fish yield by the water exchange rate [8320 kg fish/(45.9 m³/4.9 min)]. The observed loading rate was slightly higher than previous in-pond raceway studies with

Table 3Water quality variables measured in pond water samples from various collection points of an in-pond raceway system in Browns, AL. Values represent mean concentrations.

Water quality variable	Water inflow	Water outflow	Opposite end of pond
Dissolved oxygen (mg/L)	7.24	6.35	_
pН	7.83	7.75	_
TAN (mg/L)	1.34	1.43	1.45
Nitrite-N (mg/L)	0.17	0.18	0.17

catfish; $166 \, \mathrm{kg} \, \mathrm{fish/m^3/min}$ (Hawcroft, 1994), $545 \, \mathrm{kg} \, \mathrm{fish/m^3/min}$ (Bernardez, 1995), and $517 \, \mathrm{kg} \, \mathrm{fish/m^3/min}$ (Wilcox, 1998). Trout have been cultured at loading rates ranging from as $1152 \, \mathrm{to} \, 1920 \, \mathrm{kg} \, \mathrm{fish/m^3/min}$ in rectangular plug flow, circular, and cylindrical cross flow tanks (Ross et al., 1995) and tilapia at $2339 \, \mathrm{kg} \, \mathrm{fish/m^3/min}$ (Watten and Johnson, 1990). Roque et al. (2009) produced rainbow trout at loading rates of $551 \, \mathrm{kg} \, \mathrm{fish/m^3/min}$ and $276 \, \mathrm{kg} \, \mathrm{fish/m^3/min}$ in a flow through and recirculating aquaculture system, respectively.

This system was designed to maximize the use of DO naturally produced by the productivity of the pond biota by minimizing the total biomass at any given point in time. Total catfish respiration was calculated by an equation presented by Boyd et al. (1978). For example, six different size classes of fish (100 g, 200 g, 300 g, 450 g, 600 g, and 700 g) distributed based on size across the raceway units would have a total oxygen requirement for respiration of approximately 290 kg $\rm O_2/day$ at a biomass of 36,266 kg at 25 °C water temperature. If similar size fish were stocked into the raceways and allowed to reach market size (0.75 kg) at a biomass of 68,000 kg there would be a total oxygen requirement for respiration of approximately 448 kg $\rm O_2/day$ at 25 °C water temperature.

DO concentrations can be maintained without expending unnecessary energy, by estimating the total DO requirement by the fish based primarily on the total biomass and daily feed rate in a raceway. Experience with trout and other species cultured in flow-through systems indicates that for each pound of feed applied, approximately 0.2 lb of DO will be needed (Boyd et al., 2003). DO concentrations should not decline below 3.0 mg/L in catfish raceways. Thus, if the incoming water contains a mean DO concentration of 6.38 mg/L, only 3.38 mg/L DO is available (6.38 mg/L inflow - 3.0 mg/L outflow). The daily weight of the feed that can be applied can then be calculated. For example, in our study, a mean water flow rate of 9.3 m³/min per raceway and a mean DO of 6.38 mg/L was reported. In this case, the maximum daily feed input would be approximately 220 kg $[9.3 \text{ m}^3/\text{min} \times (6.38 \text{ g/m}^3 - 3.0 \text{ g/m}^3) \times 1400 \text{ min/day} \times 0.001 \text{ g/kg}]$ × 5 kg feed/kg oxygen]. The maximum feed rate can then be used to calculate the total biomass of fish that can be grown in the raceways without reducing growth due to restricted feed amount. From the above calculation and an estimated feed rate of approximately 3.0% total body weight (biomass) per day yields a maximum biomass of 7333 kg (220 kg feed/3.0% body weight/day). Thus, if the mean biomass is 8320 kg and the maximum biomass that can be grown is 7333 kg, there will be a DO requirement from the additional 987 kg of fish (8320 kg - 7333 kg). The additional feed amount and DO required will be approximately 30 kg (987 kg fish \times 3.0% body weight/day) and 6 kg (30 kg feed \times 0.2 kg DO/1.0 kg feed), respectively. The diffuser aeration device would have to be operated for approximately 3.2 h $(6.0 \text{ kg O}_2/1.88 \text{ kg O}_2/\text{h})$, use approxi-

Table 4Summary of channel catfish and hybrid catfish production in an in-pond raceway system during an 8-month period at Browns, AL.

Fish species and rearing location	Average stocking weight (g)	Total weight stocked (kg)	Number of fish stocked	Average harvest weight (g)	Total weight harvested (kg)	Total weight harvested (kg)	Production (g/fish/day)	Survival (%)	FCR
Channel catfish									
Raceway 1b	59.09	812	13,742	277.27	2515	147	1.3	66.0	1.21
Raceway 2	177.27	2082	11,745	590.91	6600	220	1.8	95.1	1.54
Raceway 5	140.91	4230	30,019	395.45	9125	193	1.1	76.9	2.11
		7124			18,240				
Hybrid catfish									
Raceway 1a	418.18	4845	11,587	640.91	7270	96	2.2	97.9	1.78
Raceway 3 (split into 3 & 4)a	240.91	4943	20,517	768.18	14,559	239	2.1	92.4	1.43
Raceway 6	61.58	1594	25,500	468.18	9844	250	1.6	82.5	1.16
		11,382			31,673				
Total weight stocked (kg)		18,506	Total weight har	vested (kg)	49,913				
			Total production	(kg)	31,407				

^a Raceway 3 reached maximum density and the decision was made to partial harvest 50% of the biomass and stock into the neighboring raceway 4. Total weight of raceway 4 was known at the time of harvest, but estimates from fish samples could only be made for the remaining fish in raceway 3.

mately 4.8 kW of electricity $(6.0 \text{ kg O}_2/1.26 \text{ kg O}_2/\text{kW h})$, and cost approximately \$0.58 (4.8 kW × \$0.12/kW h).

Raceway 3 was originally stocked with a higher number of fish and during the study a portion of the fish were removed and stocked into the neighboring raceway 4 on August 6, 2008, due to the elevated density (235 kg/m³) and associated low DO conditions. The total harvest weight of catfish was 49,913 kg for the raceways which was equal to 20,540 kg/ha for the pond into which the system was superimposed. The total harvest weight for the channel catfish and hybrid catfish was 18,240 kg (7506 kg/ha) and 31,673 kg (13,034 kg/ha), respectively (Table 4). Production in the in-pond raceway system was towards the upper range of 3456–19,382 kg/ha/year for the partitioned aquaculture system (Brune et al., 2004). In general, catfish greater than 0.454 kg were considered market size but on several occasions, smaller-sized fish were preferred over larger fish by the processing plant.

A total of 2406 kg (990 kg/ha) of paddlefish and 3959 kg (1629 kg/ha) of tilapia were harvested as co-cultured fish from the pond (Table 5). The observed paddlefish production was very high as compared to 200-400 kg/ha produced through polyculture with catfish in traditional ponds reported by Mims (2000). However, the growth rate (2.2 kg/year) of the paddlefish was slightly lower than their maximum (4.5 kg/year). Brune et al. (2004) harvested additional co-cultured tilapia of 2284–5034 kg/ha/year in a partitioned aquaculture system. The additional production for both studies was based on initial stocking of breeding pairs of tilapia, allowing them to spawn throughout the production season, and harvesting the offspring of the spawns close to the end of the season. The offspring fed on the natural primary productivity of the pond. The lower production of tilapia in the in-pond raceway system was because fewer breeding pairs were stocked as compared to the partitioned aquaculture system of Brune.

Overall survival for catfish was 83.7%. Channel catfish had a lower average survival rate (78.0%) than hybrid catfish (89.1%). This is probably the result of channel catfish contracting enteric septicemia of catfish on several occasions. Medicated feed (Aquaflor) was utilized to avoid mass mortality. Survival rates of 54.4–83.6% (Hawcroft, 1994), 67.5–81.4% (Bernardez, 1995), 58.9% (Martin, 1997), 85.6% (Wilcox, 1998) have been observed for catfish in, in-

pond floating raceways. Masser and Lazur (1997) have observed catfish survival as high as 98% for in-pond raceways. Brune et al. (2004) had excellent survival rates with channel catfish in the partitioned aquaculture system during one year. However, he reported 25–100% mortality for small fish that had to be over-wintered in the partitioned aquaculture system. This mass mortality was caused primarily by proliferative gill disease, although *Columnaris* typically was the most significant disease problem in the partitioned aquaculture system. Southworth et al. (2006a) showed that channel catfish grown under multiple-batch conditions in traditional ponds had mean survival rates ranging from 24 to 36% and 77 to 94% for fingerlings and carryover fish, respectively. Channel catfish grown under single-batch conditions in traditional ponds at different densities had mean survival rates ranging from 67 to 83% (Southworth et al., 2006b).

The average FCR for the channel and hybrid catfish was 1.74 and 1.36, respectively. This is similar to the observed FCRs for in-pond raceways of 1.85-1.95 (Hawcroft, 1994), 1.41-1.75 (Bernardez, 1995), 1.45-1.57 (Wilcox, 1998) and the partitioned aquaculture system (Brune et al., 2004); it suggests that catfish can be grown to food fish size on a commercial-scale with efficient growth rates and FCRs less than 1.8. The low FCR observed in the in-pond raceway system, partitioned aquaculture system, and floating raceways can be attributed to the manager being able to observe fish feeding, minimizing the likelihood of wasting feed. Ruane et al. (1977) and Lewis and Wehr (1976) observed much higher FCR values in heated concrete raceways and cages for catfish culture, respectively. Ruane et al. (1977) reported an average FCR of 2.23 while Lewis and Wehr (1976) observed FCRs ranging from 1.82 to 3.00. These elevated values observed with Lewis and Wehr (1976) were more than likely related to poor survival associated with parasitic outbreaks. Robinson and Li (2010) observed FCRs for channel catfish ranging from 1.79 to 2.51 produced in earthen ponds stocked at five different size-classes using traditional methods.

On commercial catfish farms, feed is applied to production ponds by mechanical, truck-mounted or tractor-drawn feeders. The operator drives the feeder around a pond and decides when enough feed has been applied before continuing on to the next pond. There is no practical way to verify if all the feed delivered

Table 5Summary of paddlefish and tilapia production as co-cultured species in an in-pond raceway system at Browns, AL.

Species	Average stocking size (kg)	Total weight stocked (kg)	Number of fish stocked	Average harvest weight (kg)	Total weight harvested (kg)	Growing period (days)	Survival (%)
Paddlefish	0.328	229.30	700	4.00	2406	675	85.9
Tilapia ^a	0.232	13.55	58	0.22	3959	203	-

a Tilapia survival was not calculated as males and females continued to spawn throughout the production season (i.e., a larger number of fish at harvest).

to the pond was consumed by the fish other than returning to the pond a second time to see if there's evidence of leftover feed, and due to this fact, excessive feed is frequently applied. Excessive feeding, along with poor survival, contributes to the high FCRs (2.2–3.0) in ponds on commercial farms as compared to FCRs below 2.0 typically obtained in research ponds where feeding is done more conservatively (Boyd and Hanson, 2010). Another factor that favors a low FCR in raceway-type systems is that fish of uniform size are stocked into individual raceways. This eliminates cannibalism that may occur under multi-batch type aquaculture practices and reduces competition or dominance of larger fish over smaller ones. In turn, the average FCR is reduced (improved) and survival is increased utilizing the single batch method. It also allows for all fish to have equal opportunities to feed in the system. Raceway-type culture has the advantage of both single batch and multiple-batch aquaculture, because uniform-sized fish are stocked in individual raceways (single-batch), while stocking different size fish in different raceways results in continual harvest typical of multiple-batch culture in ponds. This allows the producer to stock catfish segregated by size throughout the raceways. The obvious benefits from this method are continual harvest allowing for year-round cash flow and a reduction of the likelihood of exceeding the maximum carrying capacity with a resulting decline in water quality conditions that typically occurs when all catfish are stocked at once.

Growth rates ranged from 1.1 to 1.8 g/fish/day for the channel catfish and from 1.6 to 2.2 g/fish/day for the hybrid catfish. This is much lower than the growth rate of 2.63-2.77 and 2.89 g/fish/day observed in in-pond raceways and cages, respectively (Wilcox, 1998). Growth rates of 1.0-2.5 g/fish/day (Hawcroft, 1994), 3.5 g/fish/day (Bernardez, 1995) and 2.5 g/fish/day (Martin, 1997) were also observed for catfish produced within in-pond raceways. The slower growth rates observed in this study likely resulted from fish not being fed to satiation or possibly slightly underfed due to inaccurate estimations of biomass. Individuals with faster growth rates from previous studies may have been fed closer to satiation. Fish fed to satiation will have a fast growth rate, but the trade off is potential overfeeding, water quality impairment, higher FCR, and less profitability. Mean weight gain for channel catfish in traditional ponds was reported ranging from 410 g to 508 g/fish over a 125-day study for restricted and satiate feeding, respectively (Li and Lovell, 1992). Li and Lovell (1992) also found that fish fed to satiation had higher FCR than fish fed under restricted feeding

A density effect was observed with hybrid catfish in the in-pond raceway system. For example, raceway 6 had an overall yield of 179.9 kg/m³, while raceway 1a, 3a, and 4 displayed a mean yield of approximately 45.1 kg/m³. Additionally, raceways 1a, 3, and 4 were stocked with fish ranging from 0.24 to 0.42 kg each, while raceway 6 was stocked with fish that had an individual fish weight of 0.06 kg. This suggests that stocking smaller fish at a lower density would improve yield. Masser (2004) points out that higher stocking density generally increases total production, but results in smaller fish size at harvest. To increase individual fish size, stocking densities should be lower.

The total capital cost to construct the in-pond raceway system including but not limited to pond modification, foundation and wall construction, electrical panels and wiring, and storage building was \$48,301 or 19,877 per water hectare. The total equipment and machinery cost including but not limited to slow rotating paddle-wheels, diffuser aeration system, feed delivery system, automated DO monitoring system, and emergency 7.5 kW paddlewheel aerator was \$64,978 or \$26,740 per water hectare. A total capital, equipment, and machinery cost of \$113,279 or \$46,617 per water hectare was required to build and operate this production system. Due to the elevated cost associated with the modification of an existing catfish production pond to an in-pond raceway system

there is obliviously great concern with initial investment. Future research needs to focus on reducing the total capital, equipment, and machinery cost to a level which would yield a total production cost lower than traditional catfish farming production cost to make this endeavor feasible for farmers.

The in-pond raceway system was an efficient means of producing both channel catfish and hybrid catfish along with the co-culture of other species. The value of the co-cultured species could offset some of the costs for initial construction of the system. Overall survival, feed conversion ratio, and production improved in a commercial setting as compared to traditional catfish food fish production methods. Fish inventory also was more controllable because the animals were confined and easily monitored.

Acknowledgements

The authors appreciatively acknowledge financial support of this research from the Alabama Catfish Producers, Dean Wilson Farms, the Alabama Agriculture Experiment Station, and the Alabama Cooperative Extension System. Thanks also to the Alabama Fish Farming Center for providing lab and office space. The helpful assistance from Dr. Luke A. Roy and Dr. Terry R. Hanson with fish sampling and economics, respectively, was gratefully appreciated. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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