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Hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) and Nile tilapia (*Oreochromis niloticus*) culture in an integrated pen-cum-pond system: growth performance and nutrient budgets

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Abstract

Two experiments were conducted in 200-m^2 earthen ponds at Asian Institute of Technology, Thailand, for 87 days to test the feasibility of an integrated pen-cum-pond system, which utilizes wastes from intensive culture of hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) as nutrients for semi-intensive culture of Nile tilapia (*Oreochromis niloticus*). This integrated pen-cum-pond system enhances nutrient utilization efficiency, minimizes environmental impacts of pond effluents, and gains extra fish production at low cost. Experiment 1 was designed to compare the integrated pen-cum-pond systems with natural and artificial water circulation. Six randomly selected 200-m^2 ponds were partitioned by 1.0-cm mesh plastic net into two compartments: 1/3 of pond area (67 m^2) for hybrid catfish and 2/3 (133 m^2) for Nile tilapia. In experiment 2, one additional pond was partitioned by 1.0-cm mesh plastic net into three equal compartments with 67 m^2 each. The mesh was not cleaned and thus partitions serve as three replicates for hybrid catfish culture alone (non-integrated system). Experiment 2 was designed to compare growth performance of hybrid catfish and effluent quality from intensive culture of hybrid catfish among the non-integrated system with hybrid catfish alone (non-integrated treatment) and the integrated pen-cum-pond systems (natural and artificial water circulation treatments) in the 67-m^2 compartments. The nutrient budgets were also compared among the three culture systems. Sex-reversed all-male Nile tilapia were stocked at 2 fish/m^2, and hybrid catfish at 25 fish/m^2. Hybrid catfish were fed floating pelleted feed twice daily at rates of 3–10% body weight per day. During the first month, tilapia compartments were fertilized weekly using urea and

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triple superphosphate (TSP) at rates of 28 kg N and 7 kg P/ha/week. In the artificial water circulation treatment, the water in the catfish compartment was continuously circulated by a submersed pump to the tilapia compartment at a rate of one exchange per week, starting the second month.

There were no significant differences in growth performance of hybrid catfish among all treatments ($P > 0.05$). Extrapolated net tilapia yields obtained by using hybrid catfish wastes in this study were comparable to those achieved in organically and inorganically fertilized tilapia ponds. The results indicated that neither natural nor artificial water circulation between catfish and tilapia compartments improved the growth of hybrid catfish. Nile tilapia growth was not significantly different between the natural and artificial water circulation treatments ($P > 0.05$). However, the artificial water circulation caused mass mortality of Nile tilapia due to heavy loading of wastes. Nutrient budgets showed that total nitrogen (TN) and total phosphorus (TP) levels in pond effluents in the natural and artificial water circulation treatments were significantly lower than those in the non-integrated treatment ($P < 0.05$). Nile tilapia recovered 3.30% and 2.12% of TN, and 1.29% and 0.84% of TP from feed wastes and fertilizer inputs in natural and artificial water circulation treatments, respectively. Concentrations of TKN, TP and SRP were significantly lower in the natural and artificial water circulation treatments than in the non-integrated treatment ($P < 0.05$). This study demonstrates that the integrated pen-cum-pond system is feasible, indicates that Nile tilapia can effectively recover nutrients contained in wastewater of intensive catfish culture, and suggests that natural water circulation between catfish and tilapia compartments can reduce nutrient contents in pond effluents and is cost-effective.

Keywords: Nile tilapia; Hybrid catfish; Pen culture; Integrated culture; Pond; Nutrient budget

1. Introduction

Hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) has been one of the most popularly cultured freshwater fish in Southeast Asia. The present annual production in Thailand is estimated to be 50,000 tons. As an air breather, hybrid catfish can be grown at extremely high density (100 fish/m^2) with standing crop in pond culture reaching as high as 100 tons/ha (Areerat, 1987). The fish are mainly cultured intensively and fed with trash fish, chicken offal or pelleted feed, which generally cause poor water quality and heavy phytoplankton blooms throughout most of the grow-out period. To maintain tolerable water quality for fish growth, pond water is exchanged at later stages of the culture cycle (120–150 days). The effluents containing concentrated phytoplankton and nutrients, are unsuitable to irrigate rice fields because unbalanced N:P ratios (high nitrogen content) can cause fruiting failure in the rice. Wastewater disposal from hybrid catfish ponds has become a serious problem, especially in Northeast Thailand where surface waters are in short supply. Farmers often discharge wastewater to adjacent rice fields, which are damaged by this input. To fully utilize the effluents, unproductive wetlands could be excavated for Nile tilapia (*Oreochromis niloticus*) culture. Such diversification and integration are regarded as important practices to enhance aquaculture sustainability (Adler et al., 1996; Pillay, 1996).

An integrated cage-cum-pond system has been developed and practiced by Lin (1990), Lin and Diana (1995), Yi et al. (1996), Yi (1997), and Yi and Lin (2001). In the integrated cage-cum-pond system, the wastes from caged hybrid catfish have been shown to be effective for producing phytoplankton to support Nile tilapia culture in the same pond (Lin et al., 1990; Lin and Diana, 1995). Similarly, tilapia reared in cages, feeding on phytoplankton in intensive channel catfish ponds, were shown to improve pond water quality as well as produce an extra crop (Perschbacher, 1995). Alternatively, an integrated pen-cum-pond system can be established in ponds by attaching plastic netting to vertical poles inserted into pond sediments, thus partitioning a pond into two compartments. In such an integrated pen-cum-pond system, hybrid catfish can be cultured intensively with high protein feed in a compartment, while Nile tilapia can be cultured semi-intensively in the other compartment to feed on natural foods derived from catfish wastes, which pass through the netting material from the catfish compartment into the tilapia compartment.

The purposes of this study were to test the feasibility of an integrated pen-cum-pond system, which utilizes wastes from intensive culture of hybrid catfish as nutrients for semi-intensive culture of Nile tilapia. This integrated pen-cum-pond system may enhance nutrient utilization efficiency, minimize environmental impacts of pond effluents, and gain extra fish production at low cost.

2. Methods and materials

This study consisted of two experiments, which were conducted in completely randomized design in seven 200-m^2 ponds at the Asian Institute of Technology (AIT), Thailand. Experiment 1 was designed to compare the integrated pen-cum-pond systems with and without artificial water circulation. Six randomly selected 200-m^2 ponds, used as the experimental units in triplicates for each treatment, were partitioned by 1.0-cm mesh plastic net into two compartments: 1/3 of pond area (67 m^2) for hybrid catfish and 2/3 (133 m^2) for Nile tilapia. The partitioning net was brushed weekly to facilitate water exchange between compartments. In the artificial water circulation treatment, water in the catfish compartment was continuously circulated at a rate of one exchange per week to the tilapia compartment by a submersed pump, starting from the second month, while in the treatment without artificial water circulation (natural water circulation treatment), the water was naturally circulated through the partitioning net between two compartments. In experiment 2, the remained pond was partitioned by 1.0-cm mesh plastic net into three equal compartments with 67 m^2 each to serve as three replicates for hybrid catfish culture alone (non-integrated system). To minimize water exchange between the hybrid catfish compartments in the pond, the partitioning net was not brushed during the entire experimental period. Experiment 2 was designed to compare growth performance of hybrid catfish and effluent quality from intensive culture of hybrid catfish among the non-integrated system with hybrid catfish alone (non-integrated treatment) and the integrated pen-cum-pond systems (natural and artificial water circulation treatments), using 67-m^2 compartments as experimental units. The nutrient budgets were also compared among the three culture systems.

Sex-reversed all-male Nile tilapia (19.0–19.7 g in size) were stocked at 2 fish/m^2 in tilapia compartments of the natural and artificial water circulation treatments, and hybrid catfish (18.7–20.2 g in size) at 25 fish/m^2 in the non-integrated treatment and the catfish compartments of natural and artificial water circulation treatments on 3 August 1999. Hybrid catfish were fed small-, medium- and large-size floating pelleted feed (crude protein 30%, Charoen Pokphand, Bangkok, Thailand) twice daily at 0830 and 1530 h. Feeding rates of 10% body weight/day (%BWD) for hybrid catfish smaller than 20 g, 8% BWD for 20–50 g, 5% BWD for 50–100 g, and 3% BWD for fish larger than 100 g were applied 6 days per week. During the first month, tilapia compartments were fertilized weekly with urea and triple superphosphate (TSP) at rates of 28 kg N and 7 kg P/ha/week. No fertilizers were applied during the rest of experimental period. No feed was given to tilapia, which depended solely on natural foods. Water depth in all ponds was maintained at 1 m throughout the experiment by adding water weekly to replace evaporation and seepage losses.

Water quality analysis was conducted biweekly by taking integrated water column samples at 0900 h from walkways extending to the center of compartments. Pond water samples were analyzed for total Kjeldahl nitrogen (TKN), total ammonium nitrogen (TAN), nitrite-N, nitrate-N, soluble reactive phosphorus (SRP), total phosphorus (TP), total alkalinity, chlorophyll *a*, total suspended solids (TSS), and total volatile solids (TVS) using Standard Methods (APHA et al., 1985). Dissolved oxygen (DO), temperature and pH were measured at three different depths (25 cm below water surface, middle, and 25 cm above pond bottom) before taking water samples, at early morning (0600 h) and late afternoon (1600 h) using a YSI model 54 oxygen meter (Yellow Springs Instruments, Yellow Springs, OH, USA) and a Hanna model HI8424 pH meter (Hanna Instruments, Rhode Island, USA), respectively. Un-ionized ammonia-nitrogen (UIA-N) was calculated by a conversion table for given pH and temperature (Boyd, 1990).

The nutrient budgets for nitrogen and phosphorus in the three culture systems were calculated based on inputs from water, stocked fish, fertilizers and pelleted feed; and losses in harvested fish, discharged water and sediment. Sediment samples were collected with 5-cm diameter plastic tubes from top 5 cm of each compartment before initial pond filling and after fish harvest. Total nitrogen (TN) and TP in sediment samples, monthly pelleted feed samples and fish samples at stocking and harvest were analyzed using the methods described by Yoshida et al. (1976).

Average fish weights were determined biweekly by bulk weighing 40 Nile tilapia or 100 hybrid catfish randomly sampled from each compartment. All fish were harvested on 29 October 1999 after 87 days of culture. Daily weight gain (g/fish/day), yield (kg/m^2/crop) and extrapolated yield (t/ha/year) were calculated.

Data were analyzed by one-way analysis of variance (Steele and Torrie, 1980) using SPSS (version 7.0) statistical software package (SPSS, Chicago, USA). Differences were considered significant at an alpha level of 0.05. Statistical analyses for survival rates (%) were performed on arcsine transformed data. Percentages in the text were recalculated and are expressed as actual mean and confidence limits. All other means were given with $\pm$ 1 standard error (SE).

3. Results

Both hybrid catfish and Nile tilapia grew steadily in all treatments over the 87-day culture cycle. There were no significant differences in growth performance of both hybrid catfish and Nile tilapia among all treatments (P>0.05, Table 1). At harvest, hybrid catfish reached 240 ± 3.8, 238 ± 1.9, and 249 ± 7.9 g with daily weight gains of 2.53 ± 0.04, 2.51 ± 0.02, and 2.64 ± 0.09 g/fish/day in the non-integrated, natural and artificial water circulation treatments, respectively. Extrapolated net yields of hybrid catfish were 219.1 ± 4.3, 213.6 ± 3.8, and 226.7 ± 9.1 t/ha/year in the non-integrated, natural and artificial water circulation treatments, respectively. Survival rates ranged from 93.8% to 96.3%, and there were no significant differences among all treatments (P>0.05). However, the best feed conversion ratio (FCR) was achieved in the non-integrated treatment (1.25 ± 0.00) and the artificial water circulation treatment (1.26 ± 0.02) among which there was no significant difference (P>0.05), while FCRs in both treatments were significantly better than that in the natural water circulation treatment (1.31 ± 0.01) (P < 0.05). Final mean weights of Nile tilapia were 114.9 ± 14.1 and 115.0 ± 13.5 g in the natural and artificial water circulation treatments, respectively. Survival rate of Nile tilapia in the natural water circulation treatment (92%) was much higher than that in the artificial water circulation treatment (70%). However, high mortality of Nile tilapia was observed in two replicates of the artificial water circulation treatment, resulting in large variation within the treatment and no significant differences in survival of Nile tilapia between these two treatments (P>0.05). Extrapolated net yields of Nile tilapia were 7.2 ± 1.3 and 4.9 ± 0.3 t/ha/year in the natural and artificial water circulation treatments, respectively, without significant differences (P>0.05). The results indicated that neither

Table 1
Growth performance of hybrid catfish and Nile tilapia cultured in the non-integrated system (A) and integrated pen-cum-pond systems with natural (B) and artificial (C) water circulation for 87 days

Parameter	Catfish compartment			Tilapia compartment	
	A	B	C	B	C
Stocking					
Density (fish/m^2)	25	25	25	2	2
Total no. of fish	1675	1675	1675	266	266
Mean weight (g/fish)	20.0 ± 0.1	19.2 ± 0.2	19.3 ± 0.3	19.5 ± 0.1	19.1 ± 0.1
Total weight (kg)	33.5 ± 0.2	32.2 ± 0.3	32.3 ± 0.5	5.2 ± 0.0	5.1 ± 0.0
Harvest					
Mean weight (g/fish)	239.7 ± 3.8	237.8 ± 1.9	249.0 ± 7.9	114.9 ± 14.1	115.0 ± 13.5
Total weight (kg)	383.3 ± 6.6	373.3 ± 5.8	394.3 ± 14.5	28.1 ± 4.0	20.7 ± 1.0
FCR	1.25 ± 0.00[a]	1.31 ± 0.01[b]	1.26 ± 0.02[a]	–	–
Survival rate (%)	96.3 (79.6–99.4)	93.8 (88.6–97.4)	94.5 (91.6–96.8)	92.8 (65.4–99.3)	71.5 (21.2–99.9)
Gain					
Mean weight gain (g/fish)	219.7 ± 3.7	218.6 ± 2.0	229.8 ± 8.0	95.4 ± 14.1	95.9 ± 13.4
Daily weight gain (g/fish/d)	2.53 ± 0.04	2.51 ± 0.02	2.64 ± 0.09	1.10 ± 0.16	1.10 ± 0.15
Total weight gain (kg)	349.8 ± 6.8	341.1 ± 6.1	362.0 ± 14.6	23.0 ± 4.0	15.7 ± 1.0
Net yield (kg/m^2/crop)	5.2 ± 0.1	5.1 ± 0.1	5.4 ± 0.2	0.2 ± 0.0	0.1 ± 0.0
Net yield (t/ha/year)	219.1 ± 4.3	213.6 ± 3.8	226.7 ± 9.1	7.2 ± 1.3	4.9 ± 0.3
Gross yield (kg/m^2/crop)	5.7 ± 0.1	5.6 ± 0.1	5.9 ± 0.2	0.2 ± 0.0	0.2 ± 0.0
Gross yield (t/ha/year)	240.0 ± 4.2	233.8 ± 3.6	246.9 ± 9.1	8.9 ± 1.3	6.5 ± 0.3

Mean values with different superscript letters in the same row within the same compartment were significantly different (P < 0.05).

natural nor artificial water circulation between catfish and tilapia compartments improved the growth of hybrid catfish, however, artificial water circulation caused higher mortality of Nile tilapia. Based on the pond partition ratio of 2:1 for hybrid catfish and Nile tilapia culture and catfish to Nile tilapia stocking ratio of 6.3:1 in the present study, 1-ha pond could produce about 78 tons of catfish and 6 tons of tilapia per year.

Proximate compositions of inputs, sediments and fish indicate that the dominant nutrient input was the pelleted feed in all treatments (Table 2). TN and TP levels in effluents from the catfish compartments were significantly higher in the non-integrated treatment than those in the natural and artificial water circulation treatments ($P<0.05$, Tables 3 and 4). However, artificial water circulation did not significantly increase TN and TP levels in the tilapia compartments compared with natural water circulation ($P>0.05$). There were no significant differences in TN and TP contents in sediment of either catfish or tilapia compartments among all treatments ($P>0.05$). Losses of TN and TP in effluents from the catfish compartment in the non-integrated treatment were significantly higher

Table 2
Moisture, TN and TP composition (%, dry matter basis) of hybrid catfish, Nile tilapia, feeds and sediment in the non-integrated system (A) and integrated pen-cum-pond systems with natural (B) and artificial (C) water circulation for 87 days

Parameter	At stocking			At harvest		
	A	B	C	A	B	C
Catfish						
Moisture	72.04	72.04	72.04	71.82	71.58	71.23
TN	11.06	11.06	11.06	9.26	9.10	8.68
TP	1.09	1.09	1.09	2.38	2.31	2.28
Tilapia						
Moisture	–	74.40	74.40	–	78.42	79.03
TN	–	9.4	9.4	–	10.33	10.12
TP	–	0.67	0.67	–	0.81	0.80
Feed (small size)						
Moisture	4.50	4.50	4.50	–	–	–
TN	5.47	5.47	5.47	–	–	–
TP	1.04	1.04	1.04	–	–	–
Feed (medium size)						
Moisture	2.07	2.07	2.07	–	–	–
TN	5.43	5.43	5.43	–	–	–
TP	0.91	0.91	0.91	–	–	–
Feed (large size)						
Moisture	6.66	6.66	6.66	–	–	–
TN	4.59	4.59	4.59	–	–	–
TP	1.37	1.37	1.37	–	–	–
Sediment in catfish compartment						
Moisture	59.84	53.21	51.28	62.75	61.25	64.21
TN	0.23	0.24	0.20	0.29	0.32	0.25
TP	0.01	0.01	0.01	0.03	0.03	0.03
Sediment in tilapia compartment						
Moisture	–	59.13	54.11	–	62.95	63.28
TN	–	0.22	0.23	–	0.25	0.29
TP	–	0.01	0.01	–	0.04	0.03

Table 3
Nitrogen budgets in the non-integrated system (A) and integrated pen-cum-pond systems with natural (B) and artificial (C) water circulation for 87 days (unit: kg except for those indicated)

Parameter	Culture systems		
	A	B	C
Inputs			
Feed	21.339 ± 0.152	21.388 ± 0.485	21.765 ± 0.614
Fertilizers	–	2.208 ± 0.000	2.208 ± 0.000
Catfish	1.035 ± 0.005	0.997 ± 0.010	0.998 ± 0.016
Tilapia	–	0.125 ± 0.001	0.122 ± 0.001
Water in catfish compartment	0.211 ± 0.000	0.187 ± 0.008	0.225 ± 0.008
Water in tilapia compartment	–	0.441 ± 0.036	0.446 ± 0.016
Sediment in catfish compartment	4.204 ± 0.202	4.935 ± 0.386	4.621 ± 0.072
Sediment in tilapia compartment	–	7.413 ± 0.193	9.404 ± 2.014
Total	26.789 ± 0.293	37.695 ± 0.691	39.789 ± 2.492
Outputs			
Catfish	9.768 ± 0.578	9.648 ± 0.492	9.835 ± 0.240
Tilapia	–	0.629 ± 0.102	0.444 ± 0.046
Water in catfish compartment	2.440 ± 0.057[a]	0.753 ± 0.108[b]	0.776 ± 0.034[b]
Water in tilapia compartment	–	1.243 ± 0.216	1.592 ± 0.067
Sediment in catfish compartment	6.885 ± 0.256	6.804 ± 0.401	6.103 ± 0.436
Sediment in tilapia compartment	–	9.572 ± 0.291	11.916 ± 1.676
Total	19.094 ± 0.320[a]	28.649 ± 0.505[b]	30.666 ± 1.872[b]
Gain			
Catfish	8.734 ± 0.582	8.651 ± 0.495	8.837 ± 0.254
Tilapia	–	0.504 ± 0.102	0.322 ± 0.046
Loss			
Water in catfish compartment	2.229 ± 0.057[a]	0.565 ± 0.116[b]	0.551 ± 0.038[b]
Water in tilapia compartment	–	0.802 ± 0.186	1.146 ± 0.078
Subtotal in water	2.229 ± 0.057[a]	1.367 ± 0.302[b]	1.698 ± 0.115[ab]
Sediment in catfish compartment	2.682 ± 0.389	1.868 ± 0.142	1.482 ± 0.370
Sediment in tilapia compartment	–	2.159 ± 0.321	2.512 ± 0.775
Subtotal in sediment	2.682 ± 0.389	4.028 ± 0.287	3.994 ± 0.496
Unaccounted	7.695 ± 0.391	9.046 ± 0.220	9.123 ± 1.058
N required (g) to produce 1 kg fish	61.0 ± 0.79[a]	64.9 ± 0.57[b]	63.5 ± 0.71[b]
N discharged (g) to produce 1 kg fish	6.38 ± 0.26[a]	3.77 ± 0.87[b]	4.52 ± 0.41[ab]

Mean values with different superscript letters in the same row were significantly different ($P<0.05$).

than those in the natural and artificial water circulation treatments ($P<0.05$), and even significantly higher than those in the total effluents from both catfish and tilapia compartments in the natural water circulation treatment ($P<0.05$, Tables 3 and 4). Additional fertilizer inputs in the tilapia compartments of both natural and artificial water circulation treatments did not result in significantly higher nutrient outputs in effluents or nutrients deposited in sediments ($P>0.05$). Due to the additional fertilizer inputs, the nutrients (N and P) required for producing 1 kg fish including catfish and tilapia were significantly higher in the integrated pen-cum-pond system than those in the non-integrated system ($P<0.05$). However, the nutrient discharged for producing 1 kg fish was significantly higher in the non-integrated system than those in the integrated pen-cum-pond system ($P<0.05$, Tables 3 and 4).

Table 4
Phosphorus budgets in the non-integrated system (A) and integrated pen-cum-pond systems with natural (B) and artificial (C) water circulation for 87 days (unit: kg except for those indicated)

Parameter	Culture systems		
	A	B	C
Inputs			
Feed	4.938 ± 0.088	4.941 ± 0.125	5.033 ± 0.139
Fertilizers	–	0.553 ± 0.000	0.553 ± 0.000
Catfish	0.102 ± 0.001	0.098 ± 0.001	0.098 ± 0.002
Tilapia	–	0.009 ± 0.000	0.009 ± 0.000
Water in catfish compartment	0.005 ± 0.000	0.004 ± 0.000	0.005 ± 0.000
Water in tilapia compartment	–	0.008 ± 0.000	0.010 ± 0.001
Sediment in catfish compartment	0.205 ± 0.035	0.277 ± 0.049	0.283 ± 0.051
Sediment in tilapia compartment	–	0.296 ± 0.030	0.488 ± 0.140
Total	5.249 ± 0.118	6.186 ± 0.185	6.478 ± 0.315
Outputs			
Catfish	2.574 ± 0.116	2.447 ± 0.083	2.589 ± 0.158
Tilapia	–	0.050 ± 0.009	0.035 ± 0.002
Water in catfish compartment	0.151 ± 0.004^{a}	0.057 ± 0.015^{b}	0.034 ± 0.006^{b}
Water in tilapia compartment	–	0.028 ± 0.003	0.029 ± 0.004
Sediment in catfish compartment	0.833 ± 0.047	0.721 ± 0.146	0.903 ± 0.158
Sediment in tilapia compartment	–	1.305 ± 0.267	1.390 ± 0.295
Total	3.557 ± 0.098	4.608 ± 0.390	4.979 ± 0.541
Gain			
Catfish	2.472 ± 0.116	2.349 ± 0.083	2.490 ± 0.158
Tilapia	–	0.041 ± 0.009	0.026 ± 0.002
Loss			
Water in catfish compartment	0.146 ± 0.004^{a}	0.053 ± 0.015^{b}	0.029 ± 0.006^{b}
Water in tilapia compartment	–	0.020 ± 0.003	0.019 ± 0.005
Subtotal in water	0.146 ± 0.004^{a}	0.073 ± 0.018^{b}	0.048 ± 0.010^{b}
Sediment in catfish compartment	0.628 ± 0.075	0.443 ± 0.105	0.620 ± 0.107
Sediment in tilapia compartment	–	1.009 ± 0.260	0.902 ± 0.182
Subtotal in sediment	0.628 ± 0.075	1.453 ± 0.348	1.522 ± 0.247
Unaccounted	1.693 ± 0.019^{a}	1.579 ± 0.270^{b}	1.500 ± 0.256^{b}
P required (g) to produce 1 kg fish	14.1 ± 0.15^{a}	15.1 ± 0.13^{b}	14.8 ± 0.18^{b}
P discharged (g) to produce 1 kg fish	0.4 ± 0.00^{a}	0.2 ± 0.04^{b}	0.1 ± 0.03^{b}

Mean values with different superscript letters in the same row were significantly different ($P<0.05$).

Hybrid catfish incorporated 40.87%, 40.48% and 40.62% of TN, and 50.01%, 47.62% and 49.38% of TP from feed input in the non-integrated, natural and artificial water circulation treatments, respectively (Table 5). Wastes derived from feed accounted for 59.13%, 59.52% and 59.38% of TN, and 49.99%, 52.38% and 50.62% of TP from feed input in the non-integrated, natural and artificial water circulation treatments, respectively (Table 5). No significant differences in incorporated and wasted nutrients were found among all treatments ($P>0.05$). These wastes fertilized the entire pond at loading rates of 7.32 ± 0.44 and 7.43 ± 0.29 kg N/ha/day, and 1.49 ± 0.102 and 1.46 ± 0.01 kg P/ha/day in the natural and artificial water circulation treatments, respectively. Nile tilapia recovered 3.30% and 2.12% of TN, and 1.29% and 0.84% of TP from the total nutrient inputs of feed wastes and fertilizers in the natural and artificial water circulation treatments, respectively

Table 5
Distribution (%) of TN and TP in the non-integrated system (A) and integrated pen-cum-pond systems with natural (B) and artificial (C) water circulation for 87 days

Parameter	Culture systems		
	A	B	C
TN			
Catfish compartment			
Feed input	100.00	100.00	100.00
Gain in catfish	40.87 (30.58–51.58)	40.48 (29.43–52.05)	40.62 (36.23–45.06)
Wastes	59.13 (48.42–69.42)	59.52 (47.95–70.57)	59.38 (54.94–63.74)
Total	100.00	100.00	100.00
Wastes and fertilizers	100.00	100.00	100.00
Gain in tilapia	–	3.30 (1.27–6.23)	2.12 (0.84–3.96)
Effluent water	17.70 (15.81–19.67)[a]	9.90 (2.66–18.20)[b]	11.23 (7.01–16.30)[c]
Loss in sediment	21.15 (10.29–34.39)	26.91 (22.89–31.13)	26.61 (11.27–45.23)
Unaccounted	61.15 (47.90–73.61)	60.70 (53.64–67.55)	60.04 (37.51–80.54)
Total	100.00	100.00	100.00
TP			
Catfish compartment			
Feed input	100.00	100.00	100.00
Gain in catfish	50.01 (42.81–57.22)	47.62 (37.29–58.06)	49.38 (41.53–57.23)
Wastes	49.99 (42.78–57.19)	52.38 (41.94–62.71)	50.62 (42.77–58.47)
Total	100.00	100.00	100.00
Wastes and fertilizers	100.00	100.00	100.00
Gain in tilapia	–	1.29 (0.38–2.64)	0.84 (0.57–1.15)
Effluent water	5.97 (4.82–7.13)[a]	2.29 (0.80–4.40)[b]	1.54 (0.45–3.16)[b]
Loss in sediment	25.27 (15.97–35.90)	45.61 (11.36–82.23)	49.24 (17.29–81.55)
Unaccounted	68.76 (59.47–77.35)[a]	50.81 (13.23–87.91)[b]	48.38 (15.88–81.58)[b]
Total	100.00	100.00	100.00

Mean values with different superscript letters in the same row were significantly different ($P<0.05$).

(Table 5). The percentages of nutrient losses (TN and TP) in effluent water in the non-integrated treatment were significantly higher than those in both natural and artificial water circulation treatments ($P<0.05$). TN losses in effluent water were significantly lower in the natural water circulation treatment than those in the artificial water circulation treatment ($P<0.05$), while TP losses in effluent water in treatment B were significantly higher than those in the artificial water circulation treatment ($P<0.05$). No significant differences in nutrient losses (TN and TP) in sediment were found among all treatments ($P>0.05$).

Water temperature and pH throughout the experimental period in all compartments ranged from 27.6 to 31.5 °C and 6.6 to 7.4, respectively. At the end of the experiment, pH values in catfish compartments were significantly higher in the non-integrated treatment than in the natural and artificial water circulation treatments ($P<0.05$), and there were also significant differences in final pH values between the latter two ($P<0.05$, Table 6). Measured DO concentrations at dawn decreased steadily from initial levels of 1.63–3.93 to 0.17–0.30 mg/l over the 87-day culture period in all compartments, and no significant differences in final DO concentrations were found among all treatments ($P>0.05$, Table 6). Concentrations of total alkalinity, TKN, TP and SRP in catfish compartments were

Table 6
Values of water quality parameters measured at the end of the 87-day experiment in the non-integrated system (A) and integrated pen-cum-pond systems with natural (B) and artificial (C) water circulation

Parameter	Catfish compartment			Tilapia compartment	
	A	B	C	B	C
DO at dawn (mg/l)	0.20 ± 0.00	0.30 ± 0.00	0.23 ± 0.03	0.27 ± 0.03	0.17 ± 0.03
Temperature (°C)	28.0 ± 0.1	28.0 ± 0.1	28.1 ± 0.1	27.7 ± 0.1	27.9 ± 0.3
PH	7.17 ± 0.06^a	6.90 ± 0.00^c	7.10 ± 0.06^b	7.17 ± 0.06	7.10 ± 0.10
Alkalinity (mg/l)	513 ± 7^a	108 ± 7^c	155 ± 14^b	109 ± 12	135 ± 9
TKN (mg/l)	36.34 ± 0.88^a	11.16 ± 1.58^b	11.52 ± 0.53^b	9.32 ± 1.62	11.75 ± 0.47
TAN (mg/l)	3.09 ± 0.09	3.43 ± 0.07	3.76 ± 0.32	3.52 ± 0.17^x	4.13 ± 0.06^y
UIA-N (mg/l)	0.05 ± 0.01^a	0.03 ± 0.00^b	0.05 ± 0.00^a	0.04 ± 0.00	0.04 ± 0.01
Nitrite-N (mg/l)	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00^x	0.02 ± 0.00^y
Nitrate-N (mg/l)	0.07 ± 0.04	0.07 ± 0.04	0.05 ± 0.01	0.02 ± 0.02^x	0.20 ± 0.04^y
TP (mg/l)	2.25 ± 0.06^a	0.85 ± 0.23^b	0.51 ± 0.08^b	0.42 ± 0.05	0.43 ± 0.06
SRP (mg/l)	0.93 ± 0.03^a	0.01 ± 0.01^b	0.00 ± 0.00^b	0.01 ± 0.01	0.00 ± 0.00
Chlorophyll *a* (mg/m^3)	44 ± 1	72 ± 22	132 ± 57	90 ± 29	131 ± 48
TSS (mg/l)	622 ± 49	505 ± 197	190 ± 47	136 ± 27	145 ± 22
TVS (mg/l)	101 ± 5	62 ± 24	42 ± 6	30 ± 5	42 ± 11

Mean values with different superscript letters (a, b, and c, and x and y) in the same row were significantly different among catfish compartments and between tilapia compartments of the treatments, respectively ($P < 0.05$).

significantly higher in the non-integrated treatment than in the natural and artificial water circulation treatments ($P < 0.05$, Table 6). In tilapia compartments, final concentrations of inorganic nitrogen forms (TAN, nitrite-N and nitrate-N) were significantly lower in the natural water circulation treatment than those in the artificial water circulation treatment ($P < 0.05$), while there were no significant differences for other water quality parameters between the two treatments ($P > 0.05$, Table 6). UIA-N concentrations fluctuated throughout the experimental period, but increased toward the end of the experiment. There were no significant differences in final concentrations of UIA-N in catfish compartments between the non-integrated treatment and the artificial water circulation treatment ($P > 0.05$), and both were significantly higher than those in the natural water circulation treatment ($P < 0.05$, Table 6). The phytoplankton standing crop as expressed in chlorophyll *a* concentrations steadily increased over the first 2 months and decreased slightly at the end in both catfish and tilapia compartments of the natural and artificial water circulation treatments. In the non-integrated treatment, however, it increased sharply and reached the peak at the end of the second month, then decreased dramatically to a level even below those in all other compartments. At the end of the experiment, no significant differences of chlorophyll *a* concentrations were found among all compartments ($P > 0.05$, Table 6).

4. Discussion

Both natural and artificial water circulation did not improve growth of hybrid catfish compared to the non-integrated treatment in the present study. One of the most unique features of hybrid catfish is their air breathing ability, which enables them to live at extremely high population density and gives great yields in various culture systems (Lin and Diana, 1995). Extrapolated gross yield of hybrid catfish in the present study ranged from 233.8 to 246.9 t/ha/year, which was higher than those achieved in previous experiments (Lin, 1990; Ye, 1991; Lin and Diana, 1995; Sethteethunyahan, 1998), and also higher than those obtained in the traditional pond culture in Thailand (Panayotou et al., 1982; Tonguthai et al., 1993). Although the phytoplankton standing crop expressed as chlorophyll *a* concentration was significantly higher in the non-integrated treatment than in both natural and artificial water circulation treatments during most of the experimental period ($P < 0.05$), there were no significant differences in growth and yield of hybrid catfish between them ($P > 0.05$). This supported the finding by Pearl (1995) that phytoplankton-based food chain was relatively unimportant in pond culture that relies on artificial feed to promote rapid fish growth.

Artificial water circulation caused mass mortality of Nile tilapia in two replicates. The reason might be the heavy loading of wastes from the catfish compartment to the tilapia compartment, causing significantly higher concentrations of TAN than that in natural water circulation treatment ($P < 0.05$). The extrapolated tilapia yields in both natural and artificial water circulation treatments were similar to those achieved in conventional integrated fish–livestock systems (AIT, 1986), systems optimally fertilized with chicken manure (Diana et al., 1988) or chemical fertilizers (Diana et al., 1991), and fish–fish integrated culture systems (Lin, 1990; Ye, 1991; Lin and Diana, 1995; Yi et al., 1996; Yi, 1997; Yi and Lin, 2001). However, the fertilization rates by wastes from intensive culture were much higher in the present study than those reported by the above authors, due to the high ratio of hybrid catfish to Nile tilapia (6.3:1). The high loading of hybrid catfish wastes caused depletion of water quality after the first month of culture, and thus did not result in higher yields of Nile tilapia, compared to cultures with lower loading rates. The extremely higher concentrations of TKN, TAN, and TP also implied that loading rates of hybrid catfish wastes were excessive in the present study. Lowering the catfish to tilapia ratio may result in the better growth performance of Nile tilapia.

Nutrients released from the catfish compartment were about 59% of TN and 50% of TP in the present study. These were less than values reported by Boyd (1985) in channel catfish culture, or by Ye (1991) and Sethteethunyahan (1998) in a catfish–tilapia integrated culture (62% to 73% of TN and 55% to 70% of TP). The released phosphorus percentages in the present experiment were also much less than those (79–84%) calculated by Beveridge (1984) for intensive cage culture of trout.

Nile tilapia in this integrated pen-cum-pond system recovered nutrients by utilizing natural foods derived mainly from hybrid catfish wastes. The nutrient recovery percentages (2.12–3.30% of TN and 0.84–1.29% of TP) in the present study were lower than those (4–13% of TN and 5–17% of TP) reported by Ye (1991) and Lin and Diana (1995). The main reason for the low nutrient recovery was much higher ratio of hybrid catfish to Nile tilapia (6.3:1) in the present study, compared to the ratio (2.5:1) reported by them. Another reason was that the percentages in the present study included fertilizers applied to promote tilapia growth during the first month when waste loading of hybrid catfish was low. However, the percentages in the present study were higher than those (0.68–1.94% of TN and 0.86–2.48% of TP) reported by Sethteethunyahan (1998) due to the higher hybrid catfish to Nile tilapia ratio (9:1) in that experiment.

Wastewater disposal from hybrid catfish ponds has become a serious problem, especially in Northeast Thailand where surface waters are in short supply. Farmers often discharge the wastewater to adjacent rice fields, which are damaged by this input. Some farmers discharge the wastewater to adjacent wet land, causing more environmental concerns. By using the integrated pen-cum-pond system with the pond partition ratio of 2:1 for hybrid catfish and Nile tilapia culture and hybrid catfish to Nile tilapia stocking ratio of 6.3:1, 1-ha pond could produce about 78 tons of catfish and 6 tons of tilapia per year. The total fish production of about 84 tons per year in the integrated pen-cum-pond system is much lower than that (about 240 tons of hybrid catfish per year) in the catfish alone system. However, a simple economic analysis indicated that the profit was similar between the integrated pen-cum-pond system and the catfish alone system (Yi et al., 2001), while the integrated pen-cum-pond system could minimize the environmental impacts of pond effluents from intensive fish culture, giving incentives for farmers to adapt this environmentally friendly culture system.

5. Conclusion

This integrated recycling system is the first trial to develop an integrated pen-cum-pond system, which is based on the same principle of integrated cage-cum-pond system developed and practiced by Lin (1990), Lin and Diana (1995), Yi et al. (1996), Yi (1997), and Yi and Lin (2001). Compared with the cage-cum-pond system, the advantages of the pen-cum-pond system are simplicity, convenience, and low cost, however, the biggest disadvantage is that wastes derived from intensive culture may not circulate well to the semi-intensive culture system due to possible restriction of water exchange through netting materials.

The present study demonstrates that Nile tilapia can be cultured in such an integrated pen-cum-pond system to recycle nutrients in wastes which might be otherwise released into the environment, indicates that the artificial water circulation may cause mass mortality of Nile tilapia due to heavy loading of wastes, and suggests that natural water circulation between catfish and tilapia compartments can reduce nutrient contents in pond effluents and is cost-effective. The present study provides a new way for the integration of intensive and semi-intensive culture systems, which can be adapted by small-scale farmers, especially suitable for low capital investment. By using the integrated pen-cum-pond system, a portion of ponds can be used to culture high valued species to generate more income, and to efficiently utilize costly commercial or local feed through recycling feeding wastes to filter-feeding species such as Nile tilapia. Optimization of both hybrid catfish to Nile tilapia ratio, pond partition ratio, initial fertilization scheme and culture period for Nile tilapia would maximize profit, enhance nutrient utilization efficiency, and minimize environmental impacts of pond effluents.

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