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Applications of Paddle Wheel Aerators and Diffused-Air System in Closed Cycle Shrimp Farm System

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ABSTRACT

Shrimp culture practices are changing from high water exchange systems to low water exchange systems to reduce the risk of disease contamination and water pollution. The low water exchange systems require a great number of aerators to prevent water deterioration due to high organic loading associated with limited water exchange. However, high rates of aeration can not only cause excessive water currents and erode pond bottom badly but also increase power cost. In this present study, applications of paddle wheel aerators and diffused-air systems were investigated in grow-out ponds of a closed cycle farm. The results showed that these systems were successful used in shrimp production, and of the systems examined, a combination of paddle wheel and medium bubble size diffused-air system, with a polyethylene pipe network proved to be most effective and convenient. This aeration system provided suitable dissolved oxygen concentrations to the water body and the pond bottom, which could stimulate decomposition at the pond bottom. In addition, this system had low operating costs. It is suitable to be applied in low water exchange culture systems and it can also reduce problems of pond bottom erosion, a typical problem, when using large numbers of paddlewheels.

Key words: aeration, paddle wheel aerators, diffused-air system, low water exchange systems, closed cycle shrimp farm system

INTRODUCTION

The shrimp culture practices in Thailand are presently changing from high water exchange systems to low water exchange systems in order to reduce the risk of disease contamination and water pollution from external water. The low water exchange systems have to apply a great number of aerators to prevent water deterioration, which can occur associated with the limited water exchange. Nevertheless, high rates of aeration can cause excessive water currents, erode pond bottoms badly and increase sediment in the ponds. Funge-Smith and Briggs (1998) indicated that the pond soil erosion was responsible for the bulk of the accumulated sediment (88-93%) and was a major source of organic matter to the pond (40-60%). These are not only increasing the power cost but also the pond preparation cost.

In the low water exchange systems, feed usually represents more than 50% of the total variable costs of shrimp culture, seed around 10-12%, and power 10% of the cost or more, depending on the intensity of the system. However, attention to the quality and regime of feeding can reduce feed cost. Seed cost can be reduced by moderate stocking density. Pumping cost can be reduced associated with the low water exchange management. The cost

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of aeration is dependent on number of aerators, types of aerators, operating times and culture systems but it can be reduced by selection the system providing optimum dissolved oxygen and low maintenance cost without any effect on the shrimp production. Then, using the low water exchange culture system as well as the appropriate aeration management would improve an economic feasibility of the shrimp culture, especially in the closed recycle system.

In this study, applications of paddle wheel aerators and diffused-air systems were studied. The numbers of paddle wheel aerators could be decreased and replaced by diffused-air systems, which provided air to three types of diffusers positioned on the pond bottoms. These were compared to the control ponds, which were only supported by paddle wheel aerators. The study was carried out to evaluate the effect of the four aeration system types on the water and pond bottom soil qualities, survival rate, yield and feed conversion ratio in a closed cycle system shrimp farm and to develop an economic comparison of the options described.

MATERIALS AND METHODS

The experiment was conducted in a shrimp farm in Ratchaburi province, central area of Thailand during February to June 2000. This farm was chosen as it operated in closed cycle system and was about 2 hours travel from the laboratory station (Kasetsart University, Bangkok). Its size was of 16 ha water area comprising two 1.6 ha of reservoir ponds, eight grow-out ponds of 0.64 ha and two 0.8 ha treatment ponds. The remaining area was for buildings and dikes. The depth of the reservoir was 4 m, with 3 m water depth and the grow-out pond 2 m, with 1 m water depth. Apart from compensating water loss by evaporation and/or seepage, there was no water exchange in the first two months after stocking. In the third month, water exchange was approximately 10 cm every three days (i.e.10 % of total volume) and this was increased to 20 cm in the final month (20% of total volume). The water exchange was approximately 25 mm day^{-1} (2.5% of total volume per day). Effluent water was drained into two 0.8 ha treatment ponds and then to the reservoir.

Eight grow-out ponds, each of 0.64 ha (1 m water depth) were used for this experiment, based on a single-factor completely randomised experimental design with two replication ponds. Each pond was stocked with *Penaeus monodon* postlarvae sized PL 13-15 at a stocking density of 37.5 PL/m^2. Four types of aeration systems (Figure 1) were used as follows:

1) Eight long-armed paddle wheel aerators (Type I).

2) Four long-armed paddle wheel aerators combined with a diffused-air system. For this, a blower (11.7 kW ha^{-1} or 15.6 HP ha^{-1}) was employed to deliver air through a 5 cm diameter PVC pipe and then through eleven 1.5-cm diameter PE (polyethylene) pipes positioned on the pond bottom each of 60-m length with a total of 80 holes each of 1 mm diameter. The distance between each PE pipe was 5 m) (Type II). A total of 880 holes, or 1,400 holes ha^{-1} (0.0011 m^2 pore area per ha) of pond bottom was deployed.

3) Four long-armed paddle wheel aerators combined with a diffused-air system. For this a blower (11.7 kW ha^{-1} or 15.6 HP ha^{-1}) delivered air through a 5 cm diameter PVC pipe connected to a 3.5 cm diameter PVC pipe, releasing air through eight 80-cm diameter porous disks with each disk having 8,000 holes of < 1 mm diameter positioned on the pond bottom under the paddle wheel aerators) (Type III). A total of 48,000 holes, or 75,000 holes ha^{-1} (0.4125 m^2 pore area per ha) of pond bottom was deployed.

4) Four long-armed paddle wheel aerators combined with a diffused-air system. Here a blower (11.7 kW ha^{-1} or 15.6 HP ha^{-1}) delivered air through a 5 cm diameter PVC pipe, releasing air through eleven 3.5-cm diameter PVC (polyvinyl chloride) pipes of 60-m length with each pipe having 40 holes of 5 mm diameter positioned on the pond bottom.

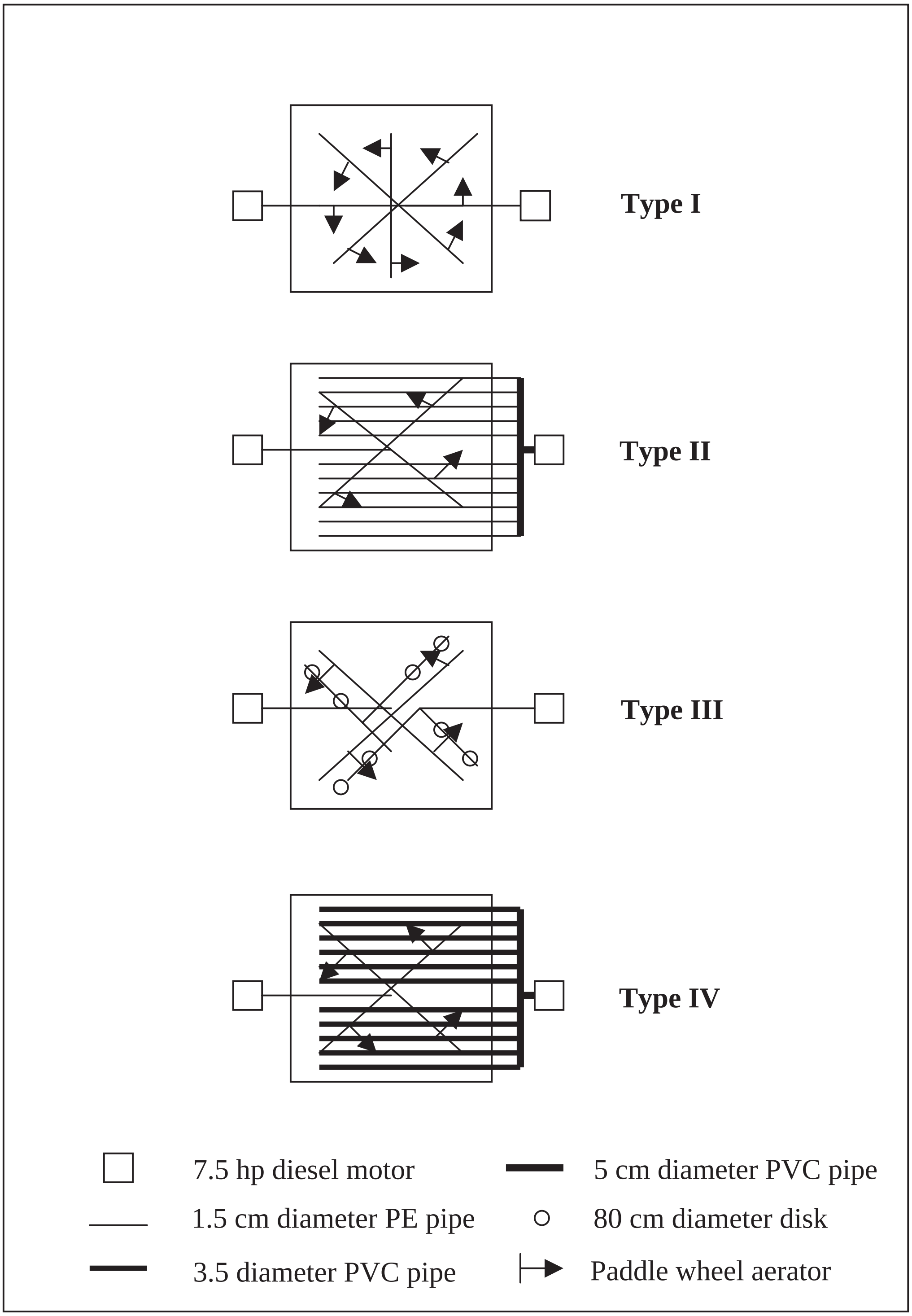

Figure 1 Aeration systems.

The distance between each PE pipe was 5 m (Type IV). A total of 440 holes m^{-2}, or 700 holes ha^{-1} (0.09625 m^2 pore area per ha) of pond bottom was deployed.

Each long-armed paddle wheel aerator consisted of a long shaft made of 2.5-3.0 cm diameter steel pipe and fitted with sixteen 60-cm diameter paddle wheels. Each paddle was 0.3 cm thick, 22 cm long and 15 cm wide. Two 10 horsepower (7.5 kW) diesel motors were used to power the paddle wheel aerators and diffused-air system in each experimental pond. The total cost (i.e., two diesel motors, paddle wheel aerators and diffuser system costs) for aeration system type I, II, III and IV was US$ 3,000, US$ 2,575, US$ 2,313 and US$ 2,450 per pond or US$ 4,688, 4,023, 3,613 and 3,828 ha^{-1}, respectively.

The schedule for aeration use for all systems was for one hour during daytime, between 13.00 to14.00 h using four paddle wheel aerators in the type I system and only the diffuser in type II, III and IV systems. At night all aerators (i.e., both paddle wheels and diffuser system) were employed from 24.00 to 6.00 h (6 hrs), 21.00 to 6.00 h (9 hrs), 21.00 to 6.00 h (9 hrs) and 18.00 to 6.00 h (12 hrs) during the 1^{st}, 2^{nd}, 3^{rd} and 4^{th} culture months, respectively. The aerators would also be run at short notice in cloudy, or rainy weather, or in the evidence of a plankton crash, but all aerators were stopped during feeding for half an hour.

Water samples were collected fortnightly at 10.00 - 12.00 h. Water parameters including salinity, temperature, Secchi disk visibility, dissolved oxygen and pH were measured in the field using field equipment. A sample of 2 L of water from each pond was taken from 50 cm below the water surface using a 100-cm water column sampler at two stations; one at the centre of the pond and the other one 3 m. from the pond dike for further analyses of alkalinity, total ammonia (NH_3-N), nitrite-ammonia (NO_2-N), nitrate-ammonia (NO_3-N), soluble orthophosphate (PO_4-P), total phosphorus (TP), suspended solids (SS), total solids (TS), dissolved solids (DS), Biochemical Oxygen Demand (BOD_5) and chlorophyll-a (Chl a) were conducted in the laboratory.

Temperature was measured using a mercury thermometer while water salinity was measured using a Salino refractometer (Atago, Model. S-28). pH was measured by pH meter (Hach Model); transparency was measured with a Secchi disk; Dissolved Oxygen (DO) was measured using a Polarographic DO meter and probe (Yellow Spring Instrument Co., Model 51B). Regarding laboratory parameters, alkalinity, Biochemical Oxygen Demand (BOD_5), total solids, dissolved solids, suspended solids, chlorophyll a and soluble reactive phosphorus (Orthophosphates) were analysed using the standard methods (APHA, 1989). Total ammonia-nitrogen was measured by the Indophenol method and nitrite-nitrogen were measured by diazotization (Grasshoff, 1974). Finally, nitrate-nitrogen and total phosphorus were analysed by the methods described by Strickland and Parson (1972).

Top 10-cm sediment samples were collected underwater monthly using a 10-cm diameter, 20-cm penetrating core sampler, at the centre and 3 m from the pond dike at the feeding area of each pond. Sediment samples were analyzed in the laboratory for total nitrogen (TN), available phosphorus (PO_4^{3-}), total ammonia nitrogen (NH_3-N), organic matter (OM), organic carbon (OC), pH and biochemical oxygen demand (BOD_5).

BOD_5 was analysed along the Standard method (APHA, 1989; and Musig and Yutharutnukul, 1991). Using this technique, 1-2 gm wet weight of sediment was diluted with sea water. The water sample in BOD bottle was incubated at 20 ° C for 5 days. Dissolved oxygen in the sample was calculated by comparing it to the dissolved oxygen in a blank sample in units of BOD_5 per 1 gm of dry sediment. From this figure, BOD_5 was calculated as mg/gm sediment. Bottom soil texture was analysed using the Hydrometer method (Kilmer and Alexander, 1949; Day, 1965). Organic matter and organic carbon were analysed by Wet oxidation (Jackson, 1958; Walkely and Black, 1934). pH was measured by pH meter (dilution of soil : water = 1 : 1). Ammonium-nitrogen was measured by mixing approximately 0.5 g of soil with 200 ml-distilled water and then supernatant was analysed by Koroleff's indophenol blue method (Grasshoff, 1974). Total nitrogen and available phosphorus were analysed by the Kjeldahl method of Murphy and Rilly, respectively (Authanam *et al.*, 1989).

The statistical analyses for the quantity and quality of water and sediment, shrimp yield, survival rate and feed conversion ratio was carried out using one-way ANOVA. In all tests, means were considered different at P<0.05. A Turkey's test was employed to compare and rank means. All statistical analyses were performed by SPSS 10.0 for Windows.

RESULTS

Water quality

The study showed significant differences in TS and DS concentrations (P<0.05) between the four aeration system applications. All other parameters (i.e., salinity, temperature, Secchi disk visibility, DO, pH, alkalinity, NH_3-N, NO_2-N, NO_3-N, PO_4^{3-}, TP, SS, BOD_5, Chl a) were not significantly different (P>0.05) (Table 1).

The type IV aeration system generated lowest levels both of total and dissolved solids, with 3,952 mg L^{-1} of TS and 3,882 mg L^{-1} of DS, while the type I aeration system was highest at 5,758 mg L^{-1} of TS and 5,676 mg L^{-1} of DS.

Other important water quality parameters were DO, NH_3-N, BOD_5 and Chl a. Aeration type I provided the highest DO levels in the ponds during

Table 1 Water quality in the ponds with different types of aeration. (Values are means* and standard deviation.)

Parameters	Aeration system			
	I	II	III	IV
Salinity (ppt)	3.9 ± 1.5	3.8 ± 1.5	3.8 ± 1.5	3.7 ± 1.5
Temperature (°C)	32.6 ± 1.4	32.7 ± 1.5	32.3 ± 1.5	32.4 ± 1.5
Secchi disk visibility (cm)	23 ± 11	19 ± 9	24 ± 13	22 ± 13
DO (mg L^{-1})	8.4 ± 1.8	8.2 ± 2.5	7.5 ± 2.9	7.1 ± 1.8
pH	8.5 ± 0.7	8.5 ± 0.6	8.8 ± 0.7	8.8 ± 0.6
Alkalinity (mg L^{-1})	105 ± 14	108 ± 19	108 ± 16	103 ± 17
NH_3-N (mg L^{-1})	0.19 ± 0.23	0.17 ± 0.18	0.18 ± 0.29	0.22 ± 0.46
NO_2-N (mg L^{-1})	0.07 ± 0.13	0.09 ± 0.12	0.07 ± 0.19	0.03 ± 0.05
NO_3-N (mg L^{-1})	0.01 ± 0.01	0.02 ± 0.04	0.00 ± 0.00	0.02 ± 0.04
PO_4^{3-} (mg L^{-1})	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.01	0.01 ± 0.01
TP (mg L^{-1})	0.15 ± 0.06	0.15 ± 0.07	0.15 ± 0.08	0.18 ± 0.13
SS (mg L^{-1})	82 ± 62	65 ± 29	58 ± 46	70 ± 55
DS (mg L^{-1})	5,676 ± 1,099(a)	5,254 ± 1,509(a)	5,111 ± 1,024(a)	3,882 ± 776(b)
TS (mg L^{-1})	5,758 ± 1,063(a)	5,319 ± 1,499(a)	5,169 ± 1,013(a)	3,952 ± 758(b)
BOD_5 (mg L^{-1})	15.1 ± 3.7	15.3 ± 4.7	15.7 ± 4.4	16.1 ± 4.7
Chl a (mg m^{-3})	122.6 ± 100.8	99.7 ± 76.2	102.6 ± 84.6	130.8 ± 150.5

* Means in the same row with followed by the same letters are not statistically different (P>0.05)

the culture cycle, followed by type II, III and IV aerators, respectively. Average DO levels in ponds with type I and II systems were 8.4 and 8.2 mg L^{-1} whilst those in types III and IV were 7.5 and 7.1 mg L^{-1}. Ponds using type IV aeration had the highest concentrations of NH_3-N, BOD and Chl a, while ponds using aeration type II had the lowest NH_3-N and Chl a concentrations.

Bottom sediment quality

The bottom sediments in all the ponds were classified as the sandy clay type (sand 47.7%, silt 14.8% and clay 37.5%). There were no significant differences (P>0.05) in bottom sediment quantity with aeration type (Table 2).

In most cases, contents of OM, OC, BOD, NH_3-N, TN, PO_4^{3-} in the sediment at the centres of the ponds were higher than at the feeding areas. However, for ponds using type III aeration, BOD_5 levels in the feeding areas were higher than in the central areas, and for ponds using type IV aeration system, NH_3-N levels in the feeding areas were higher than in the central areas. These implied that the efficiency of type III and IV systems in providing DO to the pond bottom was lower than type I and II systems. Meanwhile, pH levels were similar in feeding areas and pond centres in all experiments.

No sediment quality parameters in the pond centres differed significantly with aeration system, but organic carbon contents in feeding areas were significantly different (P<0.05) (Table 3; 4). Ponds using type II aeration had the lowest OC levels, which ponds using type I, II and IV systems had 18%, 19%, and 49% OC, respectively, which were higher than those of type II. Other parameters in these areas were not significantly different, though ponds using aeration type II had the lowest levels of OM, NH_3-N and BOD_5 contents in the feeding areas. Ponds with type IV aeration had the highest contents of OM, OC and NH_3-N, while those with type III aeration had the highest BOD levels.

System performance

Production levels, food conversion ratio and survival rate were not significantly different at P<0.05 with aeration (Table 5). The type II system obtained the highest production at 4,700 kg ha^{-1} followed by type I at 4,534 kg ha^{-1}, type IV at 4,288 kg ha^{-1} and type III at 3,883 kg ha^{-1}, respectively. Food conversion ratio was the lowest in ponds using aeration system type III at 1.26 and followed by type II, type IV and type I at 1.36, 1.40 and 1.64, respectively. Survival rate was little different between ponds using types I and III, at around 67%, while those for types II and IV were 74.2% and 77.8%, respectively. However, if the survival rate

Table 2 Bottom soil quality in the ponds with different types of aeration. (Values are means and standard deviation).

Parameters	Aeration system			
	I	II	III	IV
TN (%)	0.11 ± 0.05	0.10 ± 0.05	0.09 ± 0.05	0.09 ± 0.05
Available phosphorus (mg kg^{-1})	72.8 ± 14.7	80.3 ± 15.1	74.6 ± 21.6	77.5 ± 13.5
NH_3-N (mg g^{-1})	0.09 ± 0.07	0.09 ± 0.07	0.08 ± 0.10	0.10 ± 0.07
OM (%)	2.46 ± 1.20	2.27 ± 0.70	2.49 ± 0.85	2.90 ± 0.73
OC (%)	1.32 ± 0.45	1.34 ± 0.40	1.45 ± 0.50	1.68 ± 0.42
pH	7.25 ± 0.16	7.30 ± 0.13	7.29 ± 0.09	7.31 ± 0.10
BOD_5 (mg g^{-1})	2.54 ± 1.21	3.31 ± 2.83	3.47 ± 2.26	4.35 ± 2.60

Table 3 Bottom soil quality in the pond centres in the different types of aeration. (Values are means and standard deviation)

Parameters	Aeration system			
	I	II	III	IV
TN (%)	0.12 ± 0.06	0.12 ± 0.06	0.12 ± 0.05	0.11 ± 0.07
Available phosphorus (mg kg^{-1})	68.81 ± 19.08	84.76 ± 20.53	76.56 ± 28.08	81.12 ± 18.91
NH_3-N (mg g^{-1})	0.10 ± 0.07	0.11 ± 0.08	0.10 ± 0.14	0.08 ± 0.06
OM (%)	2.31 ± 0.91	2.65 ± 0.77	2.73 ± 1.11	2.97 ± 0.90
OC (%)	1.34 ± 0.53	1.58 ± 0.41	1.58 ± 0.64	1.72 ± 0.52
pH	7.25 ± 0.15	7.29 ± 0.13	7.32 ± 0.10	7.29 ± 0.09
BOD_5 (mg g^{-1})	2.85 ± 1.57	4.42 ± 3.16	2.88 ± 1.40	4.70 ± 3.15

Table 4 Bottom soil quality in pond feeding areas in the different types of aeration (Values are means* and standard deviation).

Parameters	Aeration system			
	I	II	III	IV
TN (%)	0.09 ± 0.04	0.08 ± 0.03	0.06 ± 0.03	0.07 ± 0.01
Available phosphorus (mg kg^{-1})	76.8 ±10.0	75.9 ± 7.4	72.6 ±17.1	73.9 ± 5.4
NH_3-N (mg g^{-1})	0.08 ± 0.08	0.06 ± 0.03	0.06 ± 0.04	0.12 ± 0.08
OM (%)	2.62 ± 1.49	1.90 ± 0.37	2.26 ± 0.45	2.82 ± 0.55
OC (%)	1.30 ± 0.38(a,b)	1.10 ± 0.22(a)	1.31 ± 0.26(a,b)	1.64 ± 0.32(b)
pH	7.25 ± 0.18	7.32 ± 0.13	7.27 ± 0.08	7.32 ± 0.12
BOD_5 (mg g^{-1})	2.23 ± 0.68	2.21 ± 2.08	4.07 ± 2.86	4.00 ± 2.08

* Means in the same row with followed by the same letters are not statistically different (P>0.05)

Table 5 Results of production, FCR, survival rate, harvested size and income of different aeration system applications (mean ± s.d.).

Aeration	Type I	Type II	Type III	Type IV
Production (kg ha^{-1})	4,534 ± 1,065	4,700 ± 71	3,883 ± 55	4,288 ± 5
FCR	1.64 ± 0.13	1.36 ± 0.11	1.26 ± 0.04	1.4 ± 0.13
Survival rate (%)	67.9 ± 19.4	74.2 ± 3.5	67.2 ± 0.4	77.8 ± 10.3
Size (individual kg^{-1})	56 ± 5	59 ± 5	65 ± 4	68 ± 2
Total revenue (US$ ha^{-1})	24,509 ± 4,705	25,278 ± 932	18,527 ± 358	19,991 ± 3,595
Culture period (days)	105	107	108	110

factor was taken out, type I system would obtain the highest production level. Average shrimp harvest size of ponds using type I system was largest at 56 shrimp kg^{-1} followed by those of type II, III and IV at 59, 65, and 68 shrimp kg^{-1}, respectively.

Financial analysis

Table 6 shows financial analysis of each aeration system. Capital cost was estimated only for the aeration system (i.e. it was assumed that capital costs of other production components were similar and hence marginal capital costs only could be compared). For type I was highest at US$ 4,688 ha^{-1} followed by type II, IV and III at US$ 4,023, 3,828, and 3,613 ha^{-1}, respectively.

Total operating costs were highest in type I ponds at US$ 7,924 ha^{-1} $crop^{-1}$ followed by type II, type IV and type III ponds at US$ 7,160, 6,892 and 6,038 ha^{-1}, respectively. These were primarily related to greater production with higher feed cost. Labour, chemical, energy and other costs did not differ between aeration systems. Total operating costs – energy cost was highest in type I at US$ 7,265 $ha^{-1}crop^{-1}$ followed by type II, IV, and III at US$ 6,484, 6,190, and 5,354 $ha^{-1}crop^{-1}$, respectively. Production per energy cost of type II was highest at 7 kg US$ followed by type I, IV and III at 6.9, 6.1 and 5.7 kg US$, respectively.

As a result of the larger harvested size in type I ponds and higher survival rate in type II ponds, these obtained more revenue than the others. Type II ponds achieved the highest average total revenue of US$ 25,278 ha^{-1}, type I obtained US$ 24,509 ha^{-1}, type IV ponds US$ 19,991 ha^{-1}, and type III ponds recorded the lowest total revenue of US$ 18,527 ha^{-1}. As a consequence, type II ponds obtained highest profit at US$ 18,118 ha^{-1} at 9%, 38%, and 45% higher than type I, IV, and III ponds, respectively.

Shrimp production (kg $crop^{-1}$) per capital

Table 6 Capital, operating costs and profit of each aeration system. Unit : US$ ha^{-1}

Items	Type I	Type II	Type III	Type IV
Capital cost				
Aeration system	4,688	4,023	3,613	3,828
Operating costs				
Feed	5,577	4,794	3,669	4,503
Seed	1,219	1,219	1,219	1,219
Energy	659	676	684	702
Labour	312	312	312	312
Others (lubricants, ice, etc.)	134	134	134	134
Chemical	23	25	20	22
Total operating costs	7,924	7,160	6,038	6,892
Production (kg ha^{-1})	4,534	4,700	3,883	4,288
Total revenue	24,509	25,278	18,527	19,991
Profit (total revenue-total operating costs)	16,585	18,118	12,489	13,099
Production/capital cost of aeration system (kg US$)	0.97	1.17	1.07	1.12
Production/ energy cost (kg US$)	6.88	6.95	5.68	6.11
Total operating costs/production (US$ $kg^{-1}ha^{-1}$)	1.75	1.52	1.55	1.61
Profit/ capital cost of aeration system	3.54	4.50	3.46	3.42

cost of aeration system (paddle wheels and/or diffused-air system costs) and per energy cost (diesel cost) was highest in type II system at 1.17 kg US$$^{-1}$ and 6.95 kg US$$^{-1}$, respectively, while type I system was lowest for production per system cost at 0.97 kg US$$^{-1}$ and type III lowest for production per energy cost at 5.68 kg US$$^{-1}$. Total operating costs per production of type II system was lowest at US$ 1.52 kg^{-1} followed by type III, IV and I systems at US$ 1.55, 1.61 and 1.75 kg^{-1}, respectively. There were no relationships between production level / profit and aeration system or energy costs.

DISCUSSION

All aeration systems showed the benefit of controlling water and sediment quality in the ponds at an acceptable level for shrimp growth, accumulating sediment in the centre of the pond and maintaining low levels of waste on the feeding area. However, most water and sediment quality parameters increased as the culture period progressed, associated with increased feed and shrimp biomass.

Comparing aeration systems, DO, TS, SS and DS concentrations in type I ponds were the highest because this system comprised of eight long-armed paddle wheel aerators, while the other systems had only four paddle wheel aerators combined with a diffused-air system. Pond water was thus overall better oxygenated but had higher solids levels. Boyd and Ahmad (1987) have evaluated aerators in shallow tanks under standard conditions of 20ºC and clean, fresh water and found that paddle wheel aerators were more efficient than other types of aerators, and diffused-air aerators had the lowest standard aeration efficiency values (SAE). Based on the calculation of average SAE values of paddle wheel aerators at 2.2 kg O_2 kW·hr^{-1} cited by Boyd (1998), type I system (operated by two 7.5 kW (10 hp) diesel motors (23 kW ha^{-1}), oxygen would be delivered approximately at 51 kg O_2 hr^{-1}ha^{-1}. Furthermore, they could produce highest levels of water circulation, as well as creating turbulence at the pond bottoms, which resulted in the highest of all the solids levels. Boyd (1992) commented that if excessive aeration were used, the bottom material would be eroded from the inside slopes of levees and around the periphery of pond bottom. These then settled to the bottom in the centre of the pond. Ponds using aeration type IV had the lowest DO, TS and DS concentrations, but highest concentrations of NH_3-N and BOD_5. This system comprised four long-armed paddle wheel aerators and a diffused-air system, with a total of 440 holes of 5 mm diameter, discharging coarse air bubbles, which are less efficient in oxygen exchange because of their smaller exchange surface area per unit of air bubble volume, and their more rapid rise in the water column. By comparison the fine air bubbles distributed by type II and III aeration produced a greater surface area to the surrounding water and allowed oxygen to diffuse into the water more effectively and rose more slowly, facilitating greater oxygen absorption.

Typical standardised aerator efficiencies (SAE) of fine, medium and coarse bubbles provided by diffused-air systems are 1.2-2.0, 1.0-1.6 and 0.6-1.2 kg O_2 kW^{-1}hr^{-1}, respectively (Colt and Orwicz, 1991). As the result of the coarse air bubbles and the smaller numbers of diffuser holes, the type IV aeration created the least pond bottom disturbance but with lower dissolved oxygen concentrations (oxygen transfer at 36 kg O_2 hr^{-1} ha^{-1}) and highest NH_3-N and BOD_5 concentrations compared to the other systems with oxygen transfer of type II (produce medium bubbles) and III (produce fine bubbles) at 41 and 44.5 kg O_2 hr^{-1}ha^{-1}, respectively. This accords with the findings of Martinez-Cordova *et al.* (1998), who noted that NH_3-N in the water is higher in ponds with lower rates of aeration as the oxidation of ammonia to nitrite, and nitrite to nitrate can occur more easily in more highly aerated conditions.

In the feeding areas of the pond, indicator levels of bottom soil quality, especially OM, OC,

NH_3-N and BOD_5 contents, were the lowest in ponds using type II aeration, and highest in type IV ponds, except for BOD_5 which was highest in type III ponds. This appeared to be because type II aeration provided oxygen directly to the pond bottom, particularly in feeding areas, which enhanced local waste oxidation and decomposition. In this case, the system (type II) was better than type I, in which water was induced to circulate only through the pond bottom surfaces. It was also better than type IV, due to the greater number and smaller diameter of diffuser holes. Though type III aeration could provide more and smaller sized air bubbles when it ran alone in the daytime, oxygen dispersion was very slow as air was produced only from the eight porous disks. These did not cover the total area of pond bottom; and therefore, this system also showed the highest BOD_5 levels.

Installation of type I system was relatively simple while types II, III and IV required the diffusion networks to be fixed or loaded on the pond bottom before filling with water, or else they would float if they have air inside the pipes. Placing of pipes on the central area of the pond should also be avoided as sediment was accumulated on this area and when a diffuser system was run, the bubbles produced could disperse accumulated waste and release toxic gases. After harvesting, polyethylene pipes (PE) especially were easy to keep and clean, and could be used in the next crop. The cost of the PE pipe network was lower than the paddlewheel and disk diffuser applications. The polyvinyl chloride (PVC) pipes system was cheapest but as noted, its disadvantage was the coarse air bubbles produced. As a practical issue, the connections also usually came loose and required higher levels of maintenance.

In comparing production, FCR and survival rate, the type II system gave the highest production and survival rate, though FCRs did not differ significantly among systems. The harvested sizes of shrimp in type I and II ponds were larger than those in type III and IV ponds. These were probably due to the higher levels of dissolved oxygen and the lower levels of waste on the pond bottoms, particularly at the feeding areas, as shrimp spend a lot of time at the bottom.

This study indicated that DO levels were not significantly different between all aeration systems. However, aeration system type II (i.e., four paddle wheel aerators + a diffuser system delivering air through eleven 880 holes and 1 mm diameter PE pipes) showed advantages over other types, including higher production and survival rate, lower installation cost, less pond bottom erosion, easier of cleaning the PE pipes for reuse in the next crop, and less waste in feeding areas. Moreover, type II system had highest returns in terms of production per energy cost and production per aeration system cost.

The type III system (i.e., four paddle wheel aerators + a diffuser system providing air through eight 48,000 holes and <1mm diameter disks produced lowest returns in production per energy cost and the type I system (i.e., eight paddle wheel aerators) had the lowest production per aeration system cost.

In the study, fixed cost was estimated only for aeration system (other fixed costs were assumed similar in each system). An interest rate was 10% annually and life span of each aeration system was four years. Thus total cost (fixed + operating costs) of type II system was US$ 8,568 ha^{-1}, 10.4% lower than type I, and 17.3% and 4.1% higher than type III and IV, respectively. Total revenue of type II was US$ 25,278 ha^{-1} which was 3.1%, 36.4% and 26.4% higher than this of type I, III and IV, respectively. Moreover, total operating costs per production of type II system was lowest at US$ 1.52 kg^{-1} ha^{-1} followed by type III, IV and I systems at US$ 1.55, 1.61 and 1.75 kg^{-1} ha^{-1}, respectively.

Thus, type II system was an alternative aeration system, which could be applied in the shrimp ponds, especially for the low water exchange systems, which had to use a great number of aerators in the ponds. Diffused-air aeration systems could release air bubbles near pond bottoms that rised to the surface causing water to move upward. Water from the surface moved downward to replace the rising water in zones where bubbles were released. These could blend supersaturated surface water with bottom waters of lower dissolved oxygen concentration and a uniform dissolved oxygen profile could be established. Nevertheless, using the diffused-air system alone in the shrimp ponds wass impractical due to lower oxygen transfer rate and less water circulation compared to the paddlewheel application. Further study should focus on the proper design of the combination of paddle wheels and a diffused-air system such as the number of paddle wheels and pipes, their positions, and number and size of the holes. A well designed aeration system could reduce the risk of oxygen depletion, mix pond water and kept the feeding areas clean with low pond bottom and walls scouring. If excessive aeration systems were used, they could cause high sediment accumulation resulting from pond bottom and walls erosion and also increased suspended solids in the water. On the other hand, if numbers of aerators used were not enough, they might be not able to maintain DO at suitable level for shrimp growth. As mentioned before, if large holes were used, they produced large air bubbles, which were less oxygen transfer efficiency compared with small holes. Howere, too small holes were also too easy to get clogged.

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LITERATURE CITED

APHA (American Public Health Association). 1989. Standard Method for the Examination of Water and Waste Water. 17th edition, American Public Health Association, Washington, D.C. 1108 p.

Authanam, T., K. Chanchareonsuk, and S. Jithagunon. 1989. Manual for Soil and Plant Analysis. Soil Science Department, Faculty of Agriculture, Kasetsart University, Bangkok. 88 p.

Boyd, C. E. 1992. Shrimp pond bottom soil and sediment management, pp. 166-181. *In* J. Wyban (ed.). Proceedings of the Special Session on Shrimp Farming. World Aquaculture Society, Baton Rouge, LA.

Boyd, C.E. and T. Ahmad. 1987. Evaluation of Aerators for Channel Catfish Farming, Bulletin 584, Alabama Agricultural Experiment Station, Auburn University, Alabama. 52 p.

Colt, J. and C.Orwicz. 1991. Aeration in intensive culture, pp.198-271. *In* E.B. David and R.T. Joseph. (eds.). Aquaculture and water quality. Advances in World Aquaculture, World Aquacult. Soc. Volume 3.

Day, P.R. 1965. Particle fraction and particle size analysis, pp. 545-567. *In* C.A. Blach. (ed.). Method of soil analysis. Part I, physical and minerabilogical properties including statistics of measurement and sampling. Agronomy, No.9. Amer. Soc. Of Agro. Inc., Madison, Wisconsin.

Funge-Smith, S.J. and M.R.P. Briggs. 1998. Nutrient budgets in intensive shrimp ponds :implications for sustainability. Aquaculture 164 : 117-133.

Grasshoff, K. 1974. Method of Sea Water Analysis. Verlag Chemic, New York. 317 p.

Jackson, M.L. 1958. Soil Chemical Analysis. Pretice-Hall, Inc., New York. 498 p.

Kilmer, V.J. and L.T. Alexander. 1949. Method of making mechanical analysis of soil. Soil Sci. 52 : 8-24.

Martinez-Cordova, L.R., H. Villarreal-Colmenares, and M.A. Porchas-Cornejo. 1998. Response of biota to aeration rate in low water exchange ponds farming white shrimp, *Penaeus vanamei* Boone. Aquacult. Res. 29 : 587-593.

Musig, Y. and P. Yuthrutyaneekul. 1991. Settling, sediment and soil quality in intensive marine shrimp farms at inner Gulf of Thailand. Fisheries Sci. 1 : 47-55.

Strickland, J.D.H. and T.R. Parsons. 1972. A Practical Handbook of Seawater Analysis. Fisheries Research Board of Canada, Ottama. 311 p.

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