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Nutrient Mass Balances in Intensive Shrimp Ponds with a Sludge Removal Regime: A Case Study in the Tam Giang Lagoon, Central Vietnam

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Abstract: Understanding the sources and sinks of nutrients is of significant importance for better management of pond water quality and the environmental impact of aquaculture. The objective of the present study was to estimate the nutrient mass balances of four intensive shrimp (*Litopenaeus vannamei*) ponds in Tam Giang Lagoon, Central Vietnam, using a sludge management regime. The nutrient budgets were calculated based on the sources and sinks of nutrients in the ponds over a period of 49 d. The input sources of N and P were mainly shrimp feed, which accounted for more than 90%. Shrimp harvesting was the largest sink of N (37.5%), but not of P (18.3%). Almost 30.4% N and 16.9% P of input were not accounted for the measured losses. While the smallest proportion of N (18.9%) was retained in sludge, the largest amount of P was accumulated in sludge (53.2%). The farm was operated without water exchange, so ponds gained only 1.9% N and 4.2% P from water intake. The pond lost about 13.2% N and 11.6% P from discharge water. Production of 1 kg shrimp needed 84.9 g N and 26.1 g P from total input sources and discharged 47.3 g N and 16.0 g P to the environment. Environmental losses of nutrients were lower or intermediate, when the loads were expressed in both kg/ha/cycle and kg of N or P per ton of shrimp produced. Furthermore, the environmental impacts of aquaculture are controlled from the system.

Key words: Shrimp pond, *L. vannamei*, nutrient mass balances, N, P.

1. Introduction

Rapid development of shrimp farming has generated considerable concerns about the effects of aquaculture pond effluents on nearby aquatic ecosystems due to increasing nutrient input [1]. Higher stocking densities of shrimp in ponds usually increases feeding rates with a concurrent increase in accumulation of sludge [2], which exacerbates problems of water quality and sediment deterioration. The water quality in ponds varies with the intensity of farming [3], and the deterioration of water quality in intensive culture ponds has been mainly related with organic matter, total nitrogen and inorganic phosphorus [4]. The feed ration is estimated from the shrimp biomass in ponds, and intensive culture requires more feed input. On the other hand, the growth of shrimp in an extensive system depends fully on natural food organisms, and in semi-intensive culture systems, both supplemental feed and natural food organisms are used [5].

According to International Union for Conservation of Nature (IUCN & IISD) [6], shrimp farms on sandy land utilize unproductive land and offer opportunities for development of methods of shrimp disease management. However, one of the biggest challenges for shrimp culture is how to simultaneously overcome environmental and economic concerns by implementing management strategies to reduce water contamination and sludge [7], because large amounts of nutrient inputs are lost to the environment [1, 8]. In response to this, enhancing nutrient recovery through

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the shrimp harvest and reducing environmental problems should be applied to intensive shrimp culture. Removing sludge accumulated at the bottom is considered to be an effective technique that can reduce up to 67% of N added as feed [9]. Furthermore, pond effluents and sludge disposal need much more attention for sustainable aquaculture development, because sludge removal takes materials out of the ponds before they are mineralized and release inorganic nutrients into the water column. Sludge removal coupled with water exchange methods is acceptable in reducing the nutrient concentration and risk of shrimp diseases. Previous works have presented methods to improve water quality and productivity of intensive shrimp ponds. So far, very few reports have described the nutrient mass balances in aquaculture on sandy lands that may have different pond bottom characteristics, especially in ponds with a sludge removal regime.

Nutrient mass balances that account for all inputs and outputs should be examined to assess environmental impacts of aquaculture [10, 11]. Many studies have calculated nutrient mass balances in extensive shrimp ponds [12], semi-intensive ponds [8, 10, 11] and intensive ponds [7, 13], while, the authors need to elucidate the nutrient budgets in the system for sustainable development. So, the objective of the present study was to estimate the nutrient mass balances for intensive shrimp culture in Tam Giang Lagoon, Central Vietnam, using a sludge management regime.

2. Materials and Methods

2.1 Study Area Description and Pond Management

Tam Giang Lagoon, located in Central Vietnam, is the largest lagoon in Southeast Asia with a total surface area of 22,000 ha [14]. Aquaculture in the lagoon has been developed since the 1970s, and shrimp culture began in the early 1990s. It quickly became a very important economic sector at the end of the 1990s and early 2000s. Farming of *L. vannamei* in Central Vietnam is more intensive (8%) than in other regions of the country [15]. The C.P. Group, belonging to the Charoen Pokphand Group of Thailand, has invested in *L. vannamei* shrimp farming on sandy land located in the North part of the lagoon (Fig. 1), Thua Thien Hue Province, Vietnam, since 2011. The shrimp farm has an area of 180 ha in total for industrial shrimp production. The first shrimp production cycle was operated in the spring from March to May 2013 (49 d). Before being transferred to grow-out ponds, post-larvae (PL) were reared with a density of 8,000 PLs/m^3 in a 300 m^2 pond in a greenhouse to the size of approximately 2,000 larvae/kg in order to minimize mortality and to reduce the grow-out culture period. Seawater was pumped directly from the sea into the pretreatment pond, and mixed with fresh groundwater to get a salinity of 28-30 ppt. Intake water was delivered to the ponds through a network of plastic pipes. *L. vannamei* shrimp were cultured at two sub-farms, A and B, consisting of 59 grow-out ponds; sub-farm C, rearing ponds in a greenhouse and sub-farm D, under construction for grow-out ponds. Four grow-out ponds at sub-farm A were randomly selected to monitor water and sludge quality and calculate nutrient mass balances. An average stocking density of shrimp in four ponds was 70 PLs/m^2. Characteristics of ponds used for mass balance estimation was described in Table 1. Shrimp were fed four times per day (07:30, 12:00, 17:00 and 22:00) with 40% crude protein commercial diet of C.P. shrimp feed [16]. The initial feeding rate was 9.5% of the biomass of each pond with adjustment according to apparent consumption through feeding trays. The daily rations were decreased to 1.5% of biomass at harvesting phase.

Fig. 2 shows the layout of the ponds used in the present study. Pond bottoms and dikes were lined with high-density polyethylene (HDPE) film to prevent water loss through seepage. Each pond had an average area of 0.43 ha, a depth of 1.4 m, and six electric aerators (12 horsepower (HP)) arranged to circulate the flow in the pond.

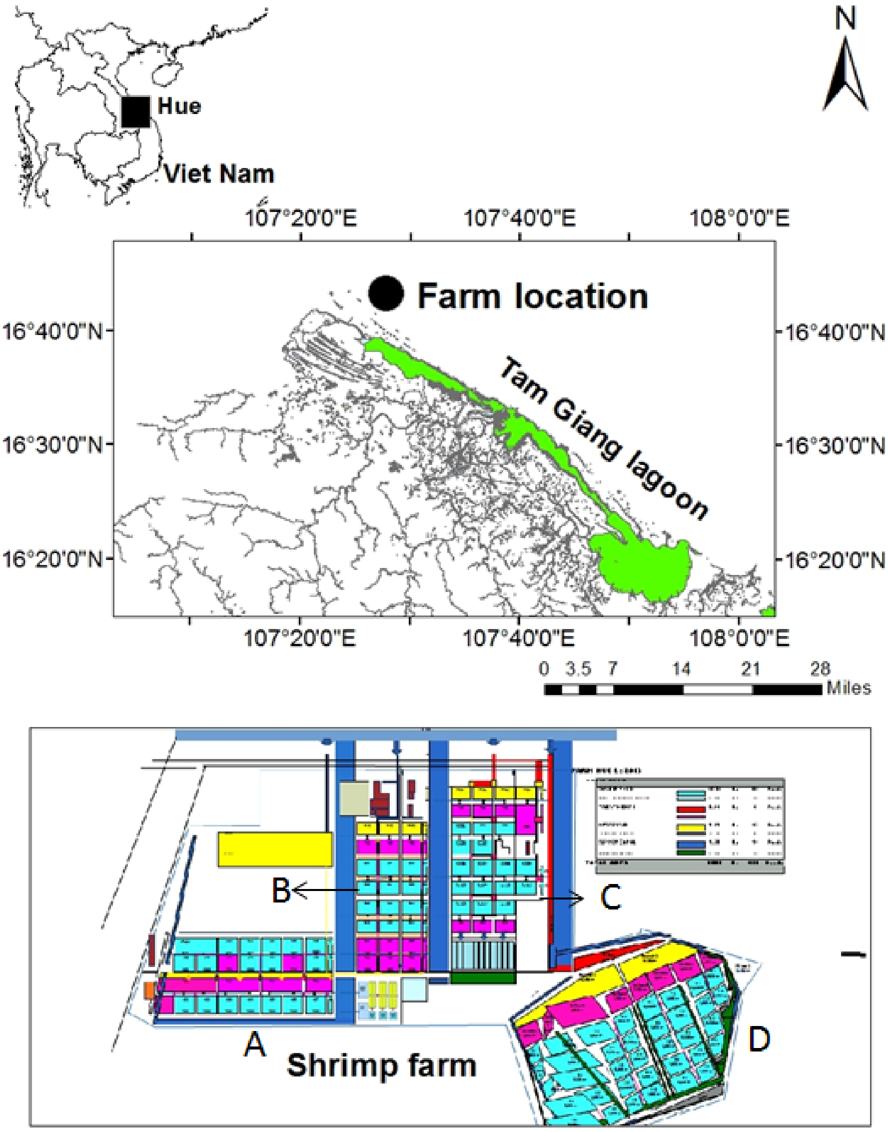

Fig. 1 Shrimp farm location.
A, B are sub-farms for grow out ponds, C is sub-farm in greenhouse for post-larvae rearing, and D is under construction for grow out.

Table 1 Characteristics of ponds for nutrients mass balance estimation.

Ponds	Density (No./m^2)	MBW (g)	Survival rate (%)	Yield (kg/ha/cycle)	FCR	Cultural period (days)	Feed used (kg/ha/cycle)
1	70.0	15.9	64	7,111.1	1.17	45.0	9,386.7
2	71.0	10.0	68	4,828.0	1.28	53.0	6,952.3
3	71.0	15.2	72	7,745.5	1.45	47.0	12,625.1
4	68.0	17.9	70	8,500.0	1.47	51.0	14,025.0
Mean	70.0 ± 1.4	16.2 ± 3.3	69.0 ± 3.4	7,046.1	1.34 ± 0.2	49.0 ± 3.7	10,747.3

MBW: mean body weight, FCR: feed conversion rate = dry weight of feed/wet weight of shrimp harvest.

In this way, sludge accumulation from uneaten feed, feces, detritus, suspended solids and dead organisms was gathered in the center of the ponds, where a drain was placed. Effluent and sludge were physically removed from the pond bottom by polyvinyl chloride (PVC) pipe lines underground connected the center of

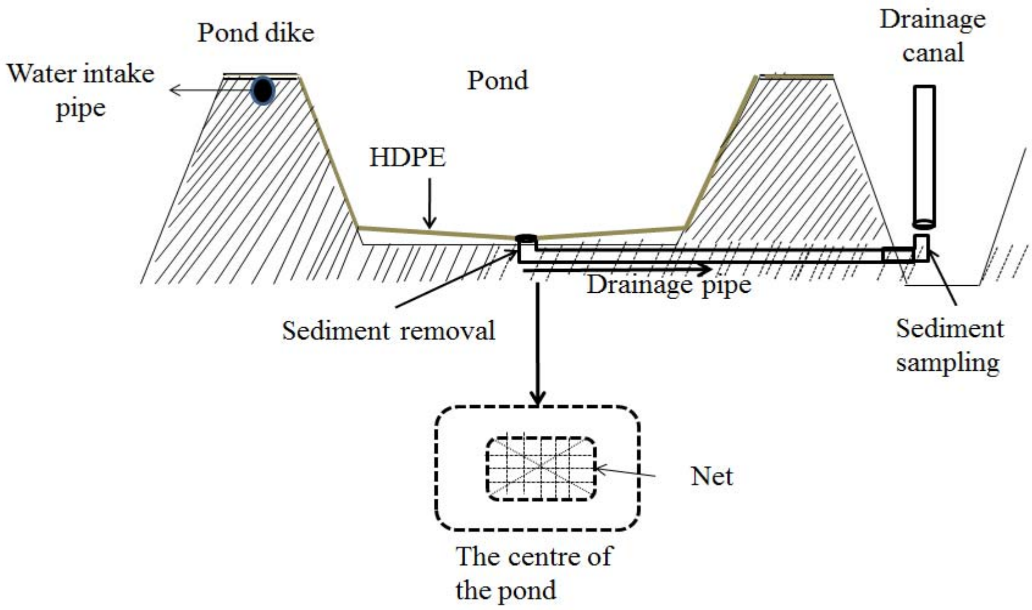

Fig. 2 Pond layout using sludge management regimes.

the ponds to an effluent canal at 20, 30, 40, and 49 d after larvae being stocked. To prevent shrimp leaving from the ponds during sludge removal, the central drain was equipped with a screen rack, an overflow mesh weir and a drain valve. This method has the advantage of allowing removal of the sludge and cleaning of the pond bottom flexibly throughout the culture period. An automatic feeding technique is used to deliver commercial feed to shrimp.

2.2 Sampling and Analytical Methods

Pond water samples were taken weekly from each pond at 20 cm below the water surface according to the method of Jackson et al. [7]. The intake water samples were collected before they entered the ponds, while the discharge samples were obtained inside the ponds before sludge was removed. The "initial" samples were those collected immediately before post-larvae stocking, and the samples collected during harvesting phase were designated as "final". Triplicate sludge samples were collected at the end of the pipe outside the pond in the drainage canal, and the water content of sludge was calculated after being dried for 24 h at 105 °C.

Water samples were filtered through a 0.2 µm filter (DISMIC-25AS, Advantec) to determine NH_4-N, NO_3-N, and PO_4-P concentrations. An unfiltered 10 mL water sample and 2 mL reagent of NaOH + $K_2S_2O_8$ for total nitrogen (TN) or 2 mL reagent of $K_2S_2O_8$ for total phosphorus (TP) were digested at 120 °C for 30 min, and the product (NO_3-N or PO_4-P) was analyzed for TN or TP [7]. The contents of TN in sludge samples and shrimp feed were analyzed by the dry combustion method using a CN Corder (MT-700, Yanaco, Japan). Approximately 1 g of air-dried sludge was digested with sulfuric acid and hydrogen peroxide at 300 °C for analysis of TP in the sludge. All water parameters were measured by the spectrophotometric method using a continuous flow auto-analyzer (QuAAtro 2-HR, Bltec, Japan). For more detail, environmental parameters and analytical methods are summarized in Table 2.

2.3 Nutrient Mass Balance Calculation

The general mass balance was calculated according to Teichert-Coddington et al. [10] as Eq. (1):

$$S_{in} + F_{in} + Fert_{in} + IPW_{in} + WI_{in} = S_{out} + PWH_{out} + WD_{out} + RS_{out} + UN \quad (1)$$

Table 2 Summary methods for analyses of parameters in water and sludge, shrimp and shrimp feed samples.

Sample parameters	Methods
Water	
Temperature (°C)	Digital thermometer *in situ*
Dissolved oxygen (mg/L)	Winkler method [1]
pH	Potentiometric method [1]
Alkalinity (mg/L)	Indophenol blue method [17]
Salinity (ppt)	Electrical conductivity method
NH_4^+-N (mg/L)	Indophenol blue method [17]
NO_3-N (mg/L)	Colorimetric method [18]
Total nitrogen (TN) (mg/L)	Digestion method [19]
PO_4-P (mg/L)	Ascorbic acid method [18]
Total phosphorus (TP) (mg/L)	Digestion and ascorbic acid method [18]
Sludge, shrimp and shrimp feed	
TN	Digestion method [8]
TP	Digestion method [8]

where *S* = shrimp, F = feed, Fert = fertilizer, IPW = initial pond water nutrients, WI = intake water nutrients, PWH_{out} = nutrients remaining at harvest, WD_{out} = nutrients in discharged water, RS_{out} = nutrients in sludge removed (dry weight) and UN = unaccounted nutrients.

The total amount of commercial shrimp feed used, quantity of sludge removed and yields of each pond were recorded. Fertilizer was not used in this study. Water intake and discharge volumes were estimated based on the measurement of water levels inside each pond. No drainage occurred during the production, and the intake water was to compensate for water losses during sludge removal. Inputs of nutrients through atmospheric rainfall and nitrogen fixation by blue-green algae were considered negligible [1, 7, 8]. The study took place in the spring, and water loss by evaporation was negligible.

3. Results and Discussion

3.1 Water and Sludge Properties

Table 3 shows the water parameters, which were measured daily on site. The commercial pelleted feed contained 6.02% N, 1.47% P and 11% water. Shrimp comprised 29.3% dry matter, 10.88% TN and 1.33% TP in the whole body. The average volumes of water losses and compensation were 30% of total pond volume for 10 d or 2.45% daily over the period. Nitrogen (NH_4-N, NO_3-N, and TN) and phosphorus (PO_4-P and TP) concentrations in the intake and discharge water increased with increasing length of culture (Table 4). These data are in agreement with those of Ma et al. [4], who also showed that nutrient concentrations in ponds increased with increasing culture period. For example, TN concentrations increased from 0.20 mg/L to 0.51 mg/L, and TP showed the same trend from 0.25 mg/L to 0.34 mg/L in the first 20 d to final day, respectively. The concentrations of TN and TP were much higher in discharge water, from 2.5 mg/L to 3.2 mg/L and 0.38 mg/L to 1.47 mg/L, respectively. On average, total food added and shrimp harvested per hectare of shrimp pond per cycle were 10,747.3 kg and 7,046.1 kg, respectively. Farm staff removed an average of 12,709 (± 3,050) kg/ha/cycle of sludge (dry weight) with concentrations of TN and TP of 8.9 g/kg and 6.2 g/kg, respectively.

3.2 Nutrient Mass Balances

The mass balances of TN and TP are shown in Table 5. The input source was mainly shrimp feed, which accounted for more than 90% of nutrient input. The present results may be comparable with other

Table 3 Water quality parameters in ponds (*n* = 4).

Temperature at 7:30/14:00 (°C)	28.9 ± 0.7/30.3 ± 0.6
Dissolved oxygen (DO) (mg/L) (at 7:30/14:00)	6.2 ± 0.1/6.5 ± 1.3
pH (at 7:30/14:00)	7.8 ± 0.2/8.0 ± 0.3
Alkalinity (mg/L)	143.6 ± 20.6
Salinity (ppt)	28.9 ± 1.9

Table 4 Nutrient concentrations of intake and discharge water and sludge samples.

Water samples	Intake water	Discharge water
NH_4^+-N (mg/L)		
20 d	0.15 ± 0.01	0.30 ± 0.02
30 d	0.14 ± 0.00	1.50 ± 0.32
40 d	0.33 ± 0.01	2.40 ± 0.02
49 d	0.33 ± 0.06	2.90 ± 0.12
NO_3-N (mg/L)		
20 d	0.025 ± 0.00	0.13 ± 0.01
30 d	0.021 ± 0.00	0.28 ± 0.01
40 d	0.036 ± 0.01	0.34 ± 0.01
49 d	0.030 ± 0.01	0.43 ± 0.00
TN (mg/L)		
20 d	0.20 ± 0.17	2.50 ± 0.53
30 d	0.24 ± 0.25	2.00 ± 0.70
40 d	0.40 ± 0.03	3.01 ± 0.12
49 d	0.51 ± 0.09	3.18 ± 0.78
PO_4-P (mg/L)		
20 d	0.03 ± 0.02	0.22 ± 0.07
30 d	0.04 ± 0.01	0.30 ± 0.02
40 d	0.08 ± 0.00	0.40 ± 0.07
49 d	0.07 ± 0.01	0.76 ± 0.01
TP (mg/L)		
20 d	0.25 ± 0.10	0.38 ± 0.07
30 d	0.28 ± 0.04	0.49 ± 0.05
40 d	0.21 ± 0.09	0.64 ± 0.01
49 d	0.34 ± 0.03	1.47 ± 0.05
Sludge samples	TN (mg/L)	TP (mg/L)
20 d	7.3 ± 0.28	4.74 ± 0.01
30 d	8.3 ± 0.28	5.06 ± 0.00
40 d	9.25 ± 0.07	7.37 ± 0.00
49 d	10.75 ± 0.35	7.66 ± 0.01

intensive shrimp ponds in Thailand [16, 20], where the majority source of the nutrient input in the pond (more than 90%) was from commercial pelleted feed. Similarly, Jackson et al. [7] reported nitrogen mass balance from intensive shrimp farm in Australia where 90% of N input was from shrimp feed. Post-larvae were reared in a greenhouse for one month before being transferred to grow-out ponds, where shrimp contributed up to 1.8% of N and 0.9% of P input. For the sinks of N in the ponds, harvested shrimp was the largest with 37.5% of total input, but not of P (18.3%). The assimilated shrimp harvest nutrients from the total inputs were higher than those in other studies [16, 20]. In an intensive shrimp system, Xia et al. [21] reported that 32.9% N and 14.2% P from total inputs were recovered from harvested shrimp, just slightly lower

Table 5 Estimation of nutrient mass balances in shrimp ponds (n = 4).

Nutrients	TN (kg/ha/cycle)	%	TP (kg/ha/cycle)	%
Input				
S_{in}	11.0 ± 0.2	1.8	1.3 ± 0.3	0.9
$Fert_{in}$	0.0	0.0	0.0	0.0
F_{in}	575.8 ± 170.9	96.2	140.6 ± 41.7	94.9
IPW_{in} + WI_{in}	11.5 ± 0.0	1.9	6.2 ± 0.0	4.2
Total	598.4	100.0	148.2	100.0
Output				
PWH_{out} + WD_{out}	78.4 ± 5.5	13.2	17.1 ± 2.1	11.6
S_{out}	224.6 ± 50.5	37.5	27.2 ± 6.1	18.3
RS_{out}	113.1 ± 27.1	18.9	78.8 ± 18.9	53.2
Un-accounted	212.7 ± 6.2	30.4	25.0 ± 17.9	16.9
Total	598.4	100.0	148.2	100.0

TN: total nitrogen, TP: total phosphorus, S_{in}: nutrients in postlarvae shrimp, $Fert_{in}$: nutrients in fertilizer, F_{in}: nutrients in shrimp feed, IPW_{in}: nutrients in pond water before shrimp stocking, WI_{in}: nutrients in water intake, PWH_{out}: nutrients remaining in pond water after harvesting, WD_{out}: nutrients in drainage water, S_{out}: nutrients in shrimp harvest, RS_{out}: nutrients in removed sediment.

than those of the present study.

About 30.4% N and 16.9% P of input were not accounted for measured losses. Nitrogen loss was attributed to denitrification and volatilization [1, 7, 10, 13]. While removed sludge retained the smallest proportion of N (18.9%), the largest quantity of P was trapped in removed sludge (53.2%). Funge-Smith and Briggs [20] showed that sludge retained 24% N and up to 84% P in intensive shrimp ponds in Thailand. Likewise, Hopkins et al. [9] reported 15%-24% N inputs for intensive ponds without sludge removal at the end of the season. Mariscal-Lagarda and Páez-Osuna [13] suggested that sludge accumulation was responsible for the sink of P in an integrated tank with shrimp and tomato.

In this study, the farm was operated without water exchange, so the pond gained only 1.9% N and 4.2% P from water intake. By contrast, approximately 13.2% N (78.4 kg/ha/cycle) and 11.6% P (17.1 kg ha/cycle) were lost from water discharge (during sludge removal). These values were in closed agreement with those from other literature, for instance, Funge-Smith and Briggs [20] reported 27% N and 10% P for the nutrient budget of discharged water. The proportions of N and P in discharge water of the present study are comparable to those of closed intensive systems, in which drainage water contained 14%-28% N and 12%-19% P [16].

Table 6 indicates that 333.2 kg N (47 kg N/ton shrimp) and 113.1 kg P (16 kg P/ton shrimp) of the nutrients for a hectare per cycle were lost to the surrounding environment. In other words, the authors' results noted that for 1 kg shrimp production needed 84.9 g N and 26.1 g P from input sources, and 47.3 g N and 16.0 g P were discharged into the environment. Similarly, Mariscal-Lagarda and Páez-Osuna [13] estimated that environmental losses of 1 kg of product harvested were 57 g N and 7.1 g P for an integrated shrimp culture.

These results were different from those of semi-intensive and extensive shrimp systems, in which ponds gained nutrients mostly from water intake and fertilizers. Water exchange in these systems is greater (11% of total pond volume per day) [8] than in an intensive system (little or no water exchange) [22]. Using fertilizers augments natural food organisms within a water body as a supplemental food for shrimp and balances the environmental conditions in ponds, because extensive and semi-intensive ponds usually do not have aerators. Islam et al. [11] reported that intake water and fertilizers accounted for 55% and 29% of total nitrogen inputs, respectively. By contrast,

Table 6 Environmental losses of nutrients for different pond systems and management methods.

Systems	N		P		References
	In kg/ha/cycle	In kg/ton	In kg/ha/cycle	In kg/ton	
Intensive systems					
P. monodon	596	92	265	41	[23]
P. monodon	764	112	213	31	[24]
P. monodon	327	93.4	–	–	[7]
L. vannamei	457	116	57	14.6	[13]
L. vannamei	333.2	47	113.1	16	This study
Semi-intensive systems					
L. vannamei	66	36	22	12	[1]
L. vannamei	19	29	8	12	[10]
P. monodon	73	111	38	58	[11]
L. vannamei (FT)	235	71	43	12	[8]
L. vannamei (FD)	214	73	38	13	[8]

FT: feeding tray, FD: feed dispersal device.

the sink of N from the shrimp harvest was only 12% and up to 78% from discharge water. The high amount of N in effluent was different from that of a water exchange procedure. However, Casillas-Hernández et al. [8] noted that more than 70% N and 50% P inputs were from shrimp feed in semi-intensive shrimp ponds, respectively.

Table 6 showed that 40.3% TN and 19.5% TP were recovered by shrimp harvest from feed added. These values were much higher than those of semi-intensive systems. For example, shrimp harvest in semi-intensive ponds assimilated only 12% TN and 3.3% reported by TP Islam et al. [11]. Likewise, Páez-Osuna et al. [1] revealed that 35.5% TN and 6.1% TP were recovered by shrimp harvest in semi-intensive ponds in Northwestern Mexico. These differences depended on nutrient sources in shrimp ponds. *L. vannamei* is an omnivorous species and it consumes diverse foods in a pond, including detritus and microorganisms. The distribution of natural foods in semi-intensive ponds is more available to shrimp, so the nutrients of inputs from other sources are converted to product (harvested shrimp).

The amounts of nutrients discharged from shrimp systems in this study are lower comparable with those in semi-intensive ponds reported by Islam et al. [11] (78 g N and 25 g P), but higher than the data of Teichert-Coddington et al. [10], who estimated approximately 16.8 g N and 2.3 g P discharge to the environment in a similar system. Environmental losses of nutrients were lower or intermediate, when the loads were expressed in both kg/ha/cycle and kg of N or P/ton shrimp. These values were lower than that reported for other intensive shrimp ponds (Table 6). However, environmental losses of nutrients in the present study were much higher than those in semi-intensive shrimp ponds when expressed as kg/ha/cycle, which indicated that higher intensity has a greater environmental impact of shrimp aquaculture.

Accordingly, the present study removed sludge periodically on days 20, 30, 40, and 49 of shrimp culture to reduce the impacts of sludge on the pond environment. Consequently, pond water was maintained in good condition for shrimp, because dissolved oxygen and ammonia gas concentrations were > 6 mg/L and < 0.1 mg/L, respectively. Furthermore, economic efficiency can be improved significantly when productivity is more than 7 tons/ha/cycle. Sludge and effluent from intensive shrimp culture and the environmental impacts of aquaculture are controlled by sludge removal, especially prevention of ground water contamination by seepage through the HDPE film at the bottom.

4. Conclusions

The present study is the first mass balance of nutrients in intensive shrimp culture on sandy land using sludge management regime. The input source nutrient in the ponds was mainly from shrimp feed. While shrimp harvest was the largest sink of N, the largest amount of P was accumulated in sludge. The results suggest that the shrimp culture in the system removed sludge periodically can be improved pond water quality. Concurrently, the environmental losses of N and P are reduced to minimize the risk of eutrophication of receiving waters.

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