

Estimating Nitrogen Discharge in Water Exchange Regimes for Super-Intensive Shrimp Farming Systems Using Nitrogen Dynamics Model

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ABSTRACT

The purpose of this study is to estimate nitrogen components and the amount of nitrogen in effluents from two super-intensive shrimp farming scenarios in Ca Mau province using the nitrogen dynamical model. The scenarios included 20% and 50% water exchange regimes at daily (a) and 15-day intervals (b) across the 90-day crop cycle. The study found that concentrations of TAN, NO_x, and dissolved nitrogen increased throughout the farming cycle under a daily water exchange system. These concentrations were interrupted during periodic water changes, resulting in a considerable reduction in the nitrogen concentration in the sediment. The total nitrogen emitted from scenario (a) was ten times that of scenario (b). Periodic water replacement in scenario (b) reduced N discharge more effectively than daily water exchange in scenario (a). More than 50% replacement would result in a nitrogen content discharge that was twice as high as 20%. Thus, reducing water exchange reduces the environmental strain.

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1. Introduction

Industrial shrimp farming has rapidly developed in the Mekong Delta region, particularly super-intensive white-leg shrimp farming in Ca Mau [1]. Increasing shrimp intensity leads to more food in shrimp ponds and more nutrients in effluent [2]. Shrimp pond waste, such as biomass left over in the pond, contains concentrated nutritional components [3]. Only around 23-30% of the nitrogen (N) in the feed was transformed into shrimp [4], [5], leaving the rest in the water and sludge that needed to be disposed of [6]. This raises serious concerns about algae blooms and eutrophication [3]. Because of N dynamics, the N concentration in shrimp ponds varies with stocking density, feeding regime, water replacement, and siphon [7]. Controlling the water exchange rate and siphoning during the shrimp farming cycle is required to avoid excessive nutrient volume in effluents into the environment [1].

Understanding the nutrient budgets was critical to developing successful nutrient management strategies for aquaculture systems, particularly shrimp pond systems [8]. Pond nutrition considers ammonium (TAN) and nitrite (NO₂⁻) concentrations, which increase with organic load [3]. The N transformation rates in aquaculture ponds could be quantified using mathematical models [9]. A mathematical model was developed to explain the N transformation rate of the key processes in shrimp farming, so N from shrimp feed occurs in water as TAN (A), dissolved N (E), nitrate/nitrite (B), and sediment (S) [10], [11]. Some research used mathematical models to investigate nitrogen dynamics in intensive shrimp ponds [11], [12], as well as differential equations for nitrogen dynamics (TAN, NO_x, and organic N) in white-leg shrimp ponds [13].

The goal of this study is to estimate N budgets using mathematical models. The models calculated N dynamics in scenarios of water exchange regimes for super-intensive shrimp farming systems in Ca Mau. The scenarios included 20% and 50% water exchange rates, as well as daily (a) and 15-day water exchange frequencies (b). This rate has largely been applied to super-intensive shrimp farming systems in Ca Mau province (<https://camau.gov.vn/>), which are compatible with the water exchange frequency used in the study of Mai et al.(2021) [14]. The outputs of the model would be used to compute total N

waste. The total N value expresses nutrient utilization efficiency, which guides proper nutrient management strategies for shrimp farming systems.

2. Materials and Methods

A mathematical model of N dynamics proposed by the authors [11], [12] for intensive shrimp (*Penaeus monodon*) farming was modified for intensive white-leg shrimp farming [13]. N transformation rates were calculated based on N input, primarily from feed, and N retention time in water (Figure 1).

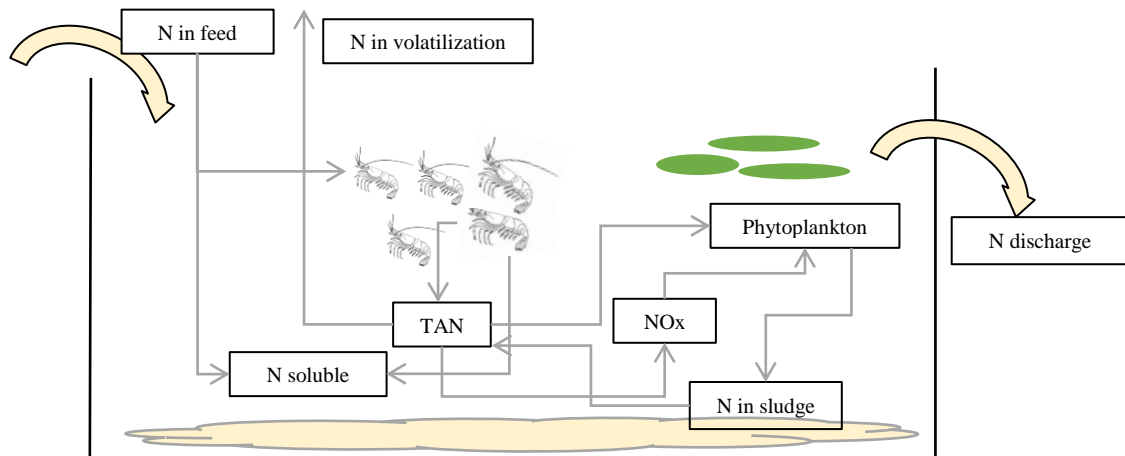


Figure 1. N transformation in shrimp ponds [10], [11], [13]

Figure 1 shows that N in feed is expelled by shrimp as TAN, while undigested feed exits as N dissolved [10], [11]. TAN can be digested by phytoplankton, released as ammonia gas, or transformed into NOx and deposited in sediments. This study employed the model to evaluate N dynamics in shrimp pond system scenarios with different water exchange rates and frequency.

This model's differential equations were applied to five state variables represented by TAN (A), NOx (B), N in sludge (S), N dissolved (E), and phytoplankton biomass (P) as described by [10], [11]. Equation (1) describes how ammonium concentrations change.

$$\frac{\Delta A}{\Delta t} = p \times T + m \times S - m' \times A - p' \times \max \times \text{Light} \times f \times P \times \left(\frac{A}{A+B+h} \right) \quad (1)$$

Where:

t: time (day);

p: ratio of N waste into water as A;

T is the TAN input per unit of time ($\text{mg} \cdot \text{g}^{-1} \cdot \text{day}^{-1}$) which is assumed to be proportional to the metabolism of the shrimp population according to formula (2).

$$T = r \times M^k \times Q_0 \times e^{-D \times t} \quad (2)$$

Where r is the value of N waste produced by one shrimp ($\text{mg} \cdot \text{g}^{-1} \cdot \text{day}^{-1}$); M is the mean weight of shrimp biomass at time t; k is metabolic coefficient of shrimp; Q_0 is the stocking density ($\text{head} \cdot \text{L}^{-1}$); D is the shrimp mortality rate (day^{-1}); A: TAN concentration ($\text{mg} \cdot \text{L}^{-1}$);

The average weight of shrimp is calculated using the growth function (3) [13]:

$$M = (M_{\max}^{1/3} - (M_{\max}^{1/3} - M_0^{1/3}) \times e^{-Kt})^3 \quad (3)$$

Where M_{\max} is growth parameters of maximum weight (g) and K is shrimp growth rate (day^{-1});

m is the remineralization rate of A in sediment (day^{-1});

S is the mass of N in sediment ($\text{mg} \cdot \text{L}^{-1}$);

m' is the nitrification rate plus the evaporation rate and water exchange rate (day^{-1});

p'_{\max} (day^{-1}) is the maximum growth rate without limitation;

Light is the light limitation coefficient according to formula (4).

$$\text{Light} = \frac{e \times \left(\exp\left(\frac{-j_0}{j_{\text{sat}}}\right) \times \exp(-((l_C \times C + l_0) \times z)) - \exp\left(\frac{-j_0}{j_{\text{sat}}}\right) \right)}{l_C \times C + l_0} \quad (4)$$

Where j_0/j_{sat} is the ratio between surface light intensity and saturation light intensity; l_C is the extinction level per unit concentration of chlorophyll-*a* ($\text{m}^{-1} \cdot \text{mg}^{-1}$) and l_0 is the extinction level due to other sources; z is the pond depth (m).

f is the ratio of N to chlorophyll content in algae; h is N half saturation;

B is the total concentration of NO_2^- and NO_3^- ($\text{mg} \cdot \text{L}^{-1}$); P is chlorophyll-*a* concentration ($\text{mg} \cdot \text{L}^{-1}$) achieved at a fixed ratio of phytoplankton N .

Change in concentration of B according to formula (5):

$$\frac{\Delta B}{\Delta t} = i \times A - r' \times B - p'_{\max} \times \text{Light} \times f \times P \times \left(\frac{B}{A+B+h} \right) \quad (5)$$

Where i is the nitrification rate; r' is the water change rate (day^{-1});

The N fixation of plants (P) in the pond ($\text{mg} \cdot \text{L}^{-1}$) is calculated using formula (6). Debris from plant biomass that can be buried in the sludge (S) is determined as the mass of nitrogen in the sludge using equation (7).

$$\frac{\Delta P}{\Delta t} = p'_{\max} \times \text{Light} \times \left(\frac{A+B}{A+B+h} \right) \times P - (r'+d) \times P \quad (6)$$

$$\frac{\Delta S}{\Delta t} = d \times f \times P - m \times S \quad (7)$$

Where $p'_{\max} \times \text{Light} \times \left(\frac{A+B}{A+B+h} \right)$ shows the growth rate of phytoplankton; d is the sedimentation rate of phytoplankton (day^{-1}).

E is the dissolved organic N ($\text{mg} \cdot \text{L}^{-1}$) remineralized from food scraps, calculated using formula (8).

$$\frac{\Delta E}{\Delta t} = (1-p) \times T - r' \times E \quad (8)$$

2.2. Data for the N dynamic mathematical model

Data utilized for the N dynamic mathematical model. A shrimp farming system in Cai Doi Vam town, Phu Tan district, Ca Mau province, was chosen as the model's case study. The system's water surface area was approximately 5000 m^3 , with the total volume of nursery ponds being 300 m^3 in the 30-day nursery stage and 4500 m^3 in the 60-day grow-up stage. Fry shrimp had an initial size of PL12 with a weight of $0.005 \text{ g} \cdot \text{shrimp}^{-1}$ and were raised at a density of $3,000 \text{ shrimp} \cdot \text{m}^{-2}$ ($600,000$ heads). Shrimp feed was industrial feed in pellet form, with a crude protein level of 42%. The water quality in the existing shrimp farming system was managed to obtain consistent input parameters, with NH_3 and NO_2^- concentrations of less than $0.3 \text{ mg} \cdot \text{L}^{-1}$, meeting the standards of Circular No. 45/2010/TT-BNNPTNT.

2.3. Calculation of N quantity discharge

The total nitrogen (TN) content in discharge did not include N components accumulated by shrimp and plants, hence it was found in shrimp pond water and sediment. Thus, the amount of TN in wastewater and sludge was determined at the end of the farming season. The TN concentration in wastewater was calculated using the volume of replenished water. In both scenarios, sewage sludge is drained daily, with an average amount of sludge accounting for 2% of the pond water content. The TN discharge indicates the effectiveness of nutrient control in the shrimp farming system. It is calculated using the formula (9).

$$\text{TN} = \sum(C_w \times V_w) + \sum(C_j \times V_j) \quad (9)$$

Where C_w is the TN concentration in wastewater (including A , B , and E); C_j is the TN concentration in sludge (including S); V_w is the volume of discharged water; and V_j is the volume of sludge.

3. Results and Discussion

Table 1 describes the factors used to estimate N components in shrimp pond systems based on mathematical calculations and practical observations taken on the farm. Some characteristics, such as the average shrimp weight, initial stocking density, shrimp mortality rate, and so on, are determined using data from the current shrimp farming system.

Table 1. Parameters for the N dynamics model for the shrimp pond system

Parameter	Unit	Value	Source
p		0.9	[13]
r	mg.g ⁻¹ .day ⁻¹	2.3	[13]
k		0.75	[13]
M ₀	g	0.005	The case study
M _{max}	g	50	The case study
K	day ⁻¹	0.0089	[13]
Q ₀	head.L ⁻¹	0.03	The case study
D	day ⁻¹	0.005	The case study
m	day ⁻¹	0.06	[11]
m'	day ⁻¹	0.25	[10], [11]
P	mg.L ⁻¹	0.032	[13]
d	ngày ⁻¹	0.8	[10], [11]
f		13	[10], [11]
p'max	day ⁻¹	1.9	[10], [11]
h	mg.L ⁻¹	0.008	[10], [11]
jo/jsat		2.4	[10], [11]
IC	m ⁻¹ .mg ⁻¹	14	[10], [11]
lo	m ⁻¹	2.5	[10], [11]
z	m	1.5	The case study
i		0.15	[13]
r'		0.05	The case study

The growth of A and E was determined by the shrimp population's metabolic processes. The average weight of shrimp was proportional to their metabolism, which was calculated using the initial stocking density Q₀. It was determined by the protein content of the food, as well as the shrimp's daily food consumption. The maximum shrimp weight was approximately 50 g. Table 2 shows the shrimp weight growth calculated using formula (3). The results showed that shrimp weight growth over time would be proportional to input A, according to formula (2). However, because the concentration of A is higher in the early days than in subsequent days, the input A drops with a negative exponential function e with time.

The content of B was mostly determined by the amount of A, whereas the abundance of phytoplankton influenced the metabolic rate of S. The concentrations of A, B, and E increased with time in both cases (Figures 2 and 3). Their concentration was comparable to the research of *Castillo-Soriano et al.* (2013) [13] and did not exceed the acceptable limit for surface quality. In these figures, the B concentration was lower than the A concentration due to the original B concentration being subtracted using formula (5). Furthermore, high water exchange rates would reduce B, resulting in B being lower in scenario (b) than in scenario (a). Similar to B, the change in E is dependent on the input A, hence the E concentration is smaller than the A concentration. Furthermore, high water exchange rates lower the amount of E.

Table 2. Shrimp volume growth and A content

Day	W (g.con ⁻¹)	A (mg.L ⁻¹)
1	0.008	0.002
5	0.034	0.006
10	0.104	0.014
15	0.227	0.025
25	0.663	0.053
30	0.983	0.069
45	2.355	0.122
60	4.287	0.175
75	6.665	0.225
90	9.355	0.267

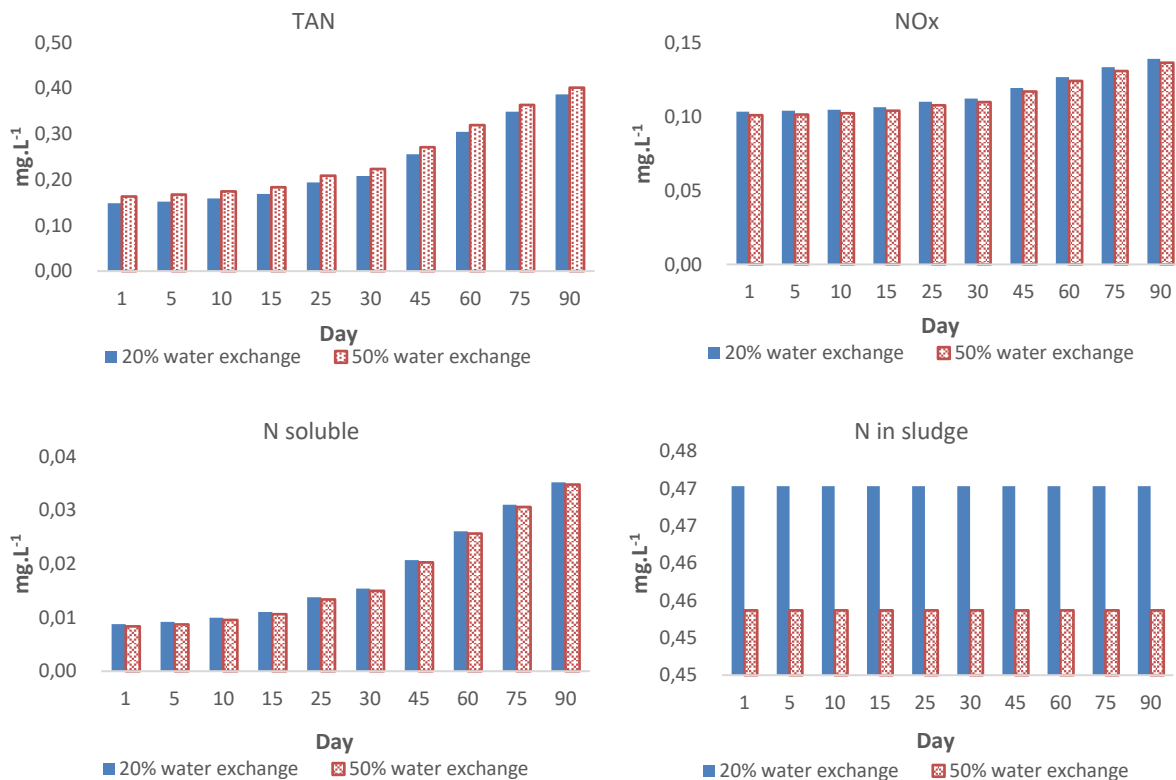


Figure 2. Concentration of N components over time in scenario (a)

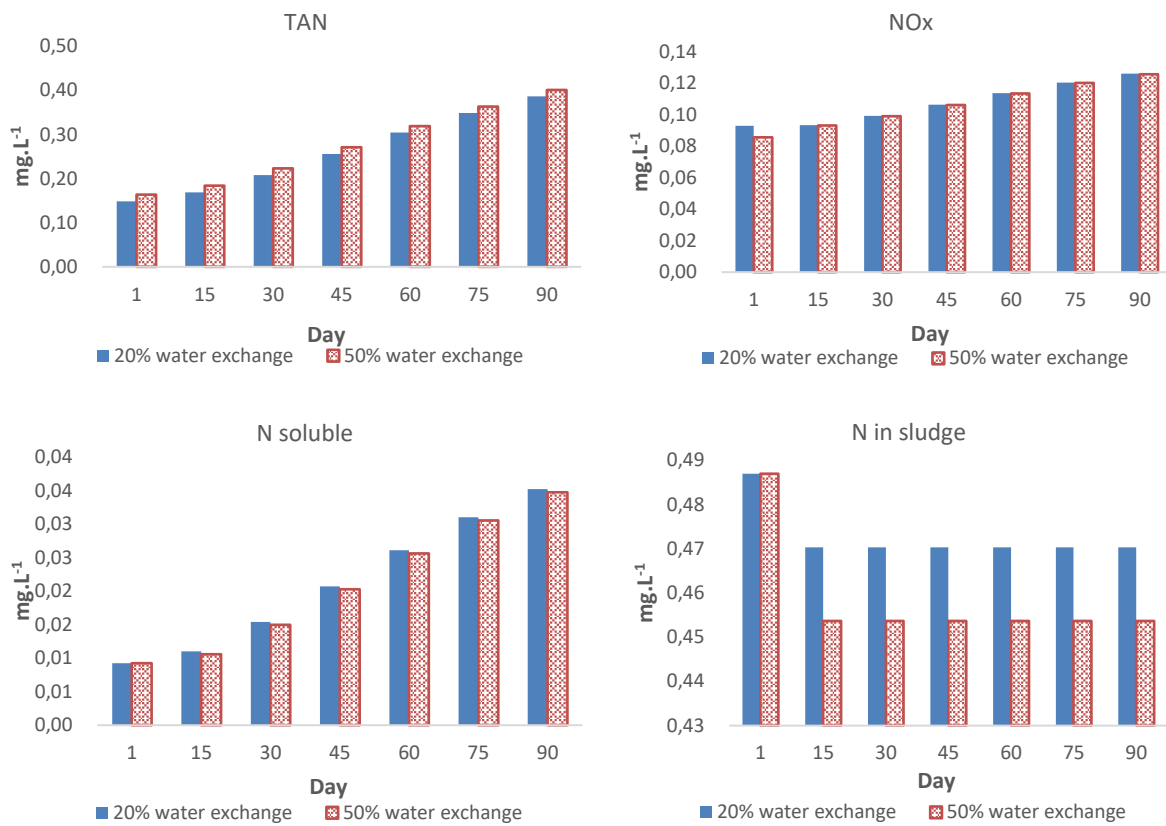


Figure 3. Concentration of N components over time in scenario (b)

The concentration of S changed little due to its reliance on algae, remaining steady in scenario (a) but abruptly falling during water exchange in scenario (b). The findings were congruent with those of *Burford and Lorenzen (2004)* [11]. Increasing the water exchange rate reduced N in algae (P), as well as N in sludge (s), and exchange rates more than 30% per day caused S content to disappear. Similarly, the change in NOx concentration in scenario (b) was slightly higher than in scenario (a) due to the periodic water replacement.

Table 3. TN amount discharged (kg) during the shrimp farming cycle in two scenarios

Water regime	Waste source	(a) Daily exchange		(b) Periodical water exchange	
		Nursery stage	Grow-up stage	Nursery stage	Grow-up stage
20% water exchange	Wastewater	1318.34	46869.95	92.92	3390.76
	Sludge	84.66	2539.69	84.66	2629.55
	Total	1403.00	49409.64	177.59	6020.31
50% water exchange	Wastewater	3264.37	116224.43	236.82	8611.91
	Sludge	81.66	2449.84	81.66	2629.55
	Total	3346.03	118674.26	318.48	11241.45

The N content in discharge would differ depending on the N dynamics in the pond in each scenario. The difference in water change rates would impact the concentrations of B, E, and S (as illustrated in figures 4 and 5), resulting in a change in TN in discharge. Furthermore, the frequency of water changes due to discharge volume would alter the TN content. This study took into account the TN in waste from both nursery and grow-up settings. In scenario (a), with a 20% water exchange rate, the amount of nitrogen in wastewater rose by 0.15 g and 3.2 g per day in the nursery and growth stages, respectively (Figure 4). With a 50% rate, the rise is threefold in both stages. In scenario (b), total nitrogen in wastewater grew consistently throughout the stages, only decreasing at water replacement intervals (Figure 5).

Because sludge was collected daily, the TN content in sludge remained consistent in both scenarios, accounting for approximately 2 g and 40 g per day in the nursery and grow-up periods, respectively.

Table 3 presents the total nitrogen emitted throughout a 90-day shrimp growing cycle in the two scenarios. In scenario (a), the TN quantity under 20% and 50% water exchange regimes was 51 kg and 123 kg, respectively, whereas in scenario (b), it was 6 kg and 12 kg.

The results demonstrate that a daily water exchange rate greater than 50% resulted in twice as much TN discharge as a 20% rate. Furthermore, water exchange frequency of 5-6 times every crop cycle would lower this TN quantity. As a result, the environmental burden is minimized when water exchange is limited or eliminated during the shrimp farming process [2], which reduces nutrient leakage into the environment.

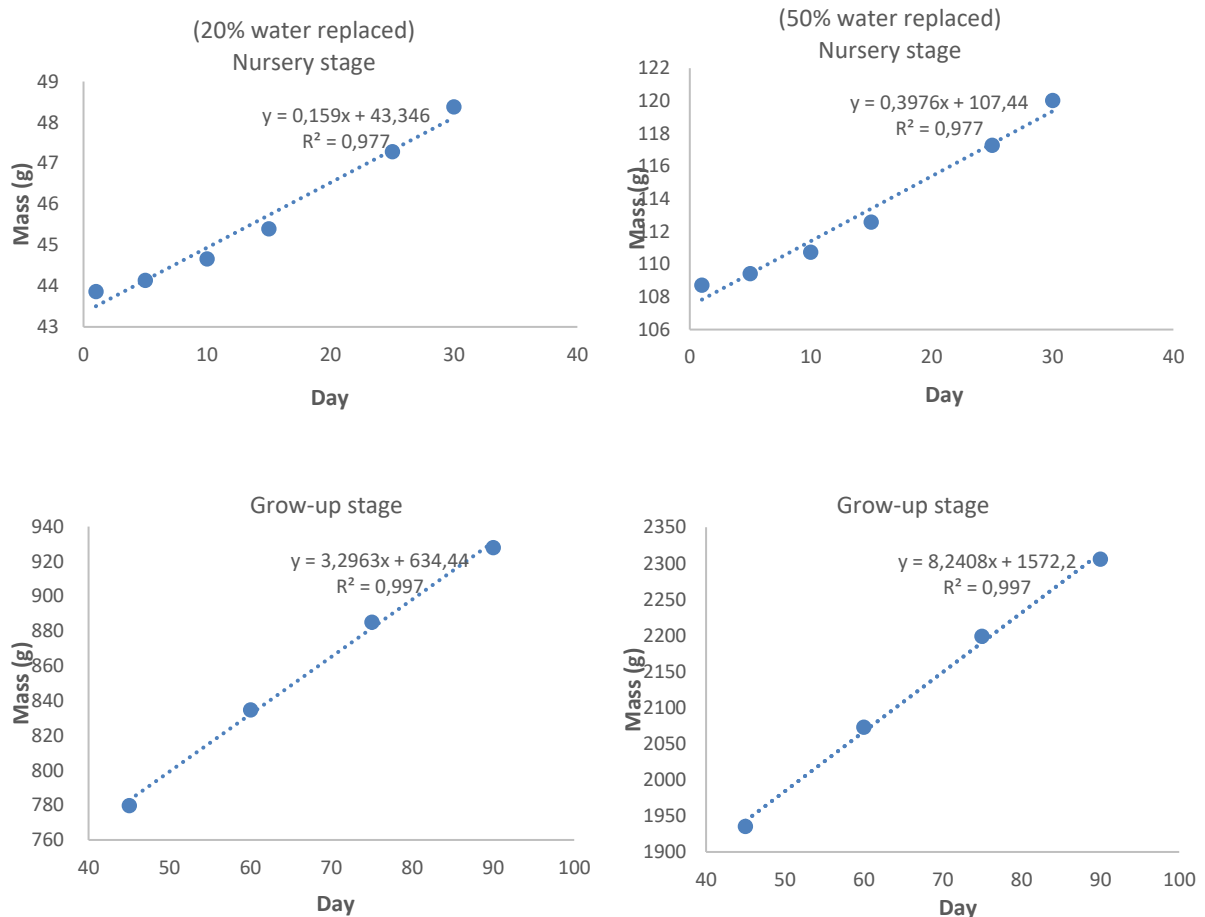


Figure 4. Graph of N content change in wastewater over time in scenario (a)

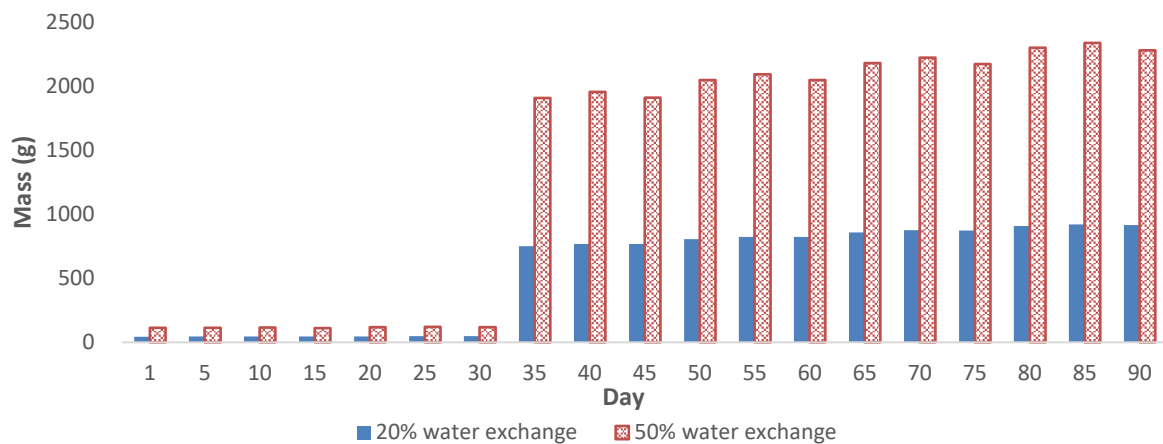


Figure 5. *N* content change in wastewater in scenario (b)

4. Conclusions

The difference in water exchange regime and frequency in super-intensive shrimp ponds had a substantial effect on the total N contained in discharge. This work assessed the contents of N components using a mathematical model of N dynamics. The study's findings revealed that TAN, NO_x, and dissolved N concentrations increased at the same rate throughout the culture cycle. As a result, the amount of TN in discharge increased twofold when the water exchange rate was increased to 50% from 20%. The daily water exchange scenario would result in a far larger N discharge amount (10 times) than the intermittent water exchange scenario. Thus, minimizing water replacement during shrimp farming is critical for reducing excessive nutrient emissions. The study's findings suggested that managing feeding with sufficient nutrition content, together with proper water exchange regimes, would be an important technique for addressing the problem of nutritional pollution created by existing shrimp farming practices.

Abbreviation

A: Ammonium, B: Nitrite and Nitrate; C: Chlorophyll-a; E: Dissolved Nitrogen; N: Nitrogen; S: Nitrogen in sediment.

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Conflict of Interest

The author declares no conflict of interest.

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