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Water Quality and Plankton Dynamics as Determinants of Ecosystem Stability in Intensive Culture of Whiteleg Shrimp (*Litopenaeus vannamei*)

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ABSTRACT

Intensive vannamei shrimp farming requires stable water quality because changes in water conditions can affect plankton abundance, which supports the ecological balance of the pond. This relationship provides a basis for managing productive and sustainable aquaculture systems. This study aimed to analyze water quality conditions, plankton abundance, and the relationship between the two in an intensive farming system of vannamei shrimp (Litopenaeus vannamei) at PT. Dua Putra Perkasa, Kaur Regency, Bengkulu, Indonesia. The study employed an observational survey method in seven intensive vannamei shrimp ponds throughout one 72-day culture cycle. We measured water quality periodically and analyzed plankton abundance through laboratory identification. We analyzed all data descriptively and comparatively to evaluate the relationship between water quality and plankton abundance. The results showed that all measured ecological parameters remained within the optimal ranges for intensive vannamei shrimp farming, including temperatures of 26.9–31.5°C, pH values of 7.5–8.2, a mean dissolved oxygen (DO) concentration of 4.6 mg/L, water transparency of 30–40 cm, and salinity of 30–34 ppt. These conditions supported shrimp physiological processes and biogeochemical activities in the ponds. NH_4^+ and NO_2^- concentrations increased during several periods, indicating increasing nutrient pressure as farming intensity increased. Plankton abundance ranged from 204,000 to 440,000 cells/L and was dominated by green algae (GA), particularly Chlorella sp. and Tetraselmis sp., followed by diatoms (Navicula, Nitzschia, Bellerochea, and Chaetoceros) and minor dinoflagellates. In contrast, Cyanophyta and dinoflagellates occurred at relatively low proportions. Pond stability depends not only on water quality but also on the balance of nutrient inputs, biogeochemical transformations, and nutrient utilization by plankton. Therefore, integrated monitoring of water quality and plankton community structure is essential for maintaining the productivity and sustainability of intensive L. vannamei farming.

***Keywords**: aquaculture, nitrate, phosphate, phytoplankton*

INTRODUCTION

Whiteleg shrimp (*Litopenaeus vannamei*) is one of the world's most important aquaculture commodities and contributes substantially to aquaculture production and seafood exports in many countries, including Indonesia (Amiin et al., 2023; Mustafa et al., 2022; Nisa et al., 2023; Supono & Rivaie, 2025). The increasing global demand for shrimp has encouraged producers to adopt intensive farming systems with high stocking densities to maximize production efficiency and economic returns. However, intensive production also accelerates the accumulation of uneaten feed, feces, and other organic residues, which can progressively deteriorate water quality when pond management is inadequate (Jescovitch et al., 2018; Joffre et al., 2018). Such environmental deterioration adversely affects shrimp growth, increases disease susceptibility, and ultimately reduces production performance (Alfiansah et al., 2018; Ariadi et al., 2025; Emerenciano et al., 2022; Ng et al., 2018). Moreover, high shrimp biomass, intensive feeding practices, and the continuous accumulation of metabolic wastes impose considerable ecological pressure on pond ecosystems by altering their physicochemical characteristics and biological processes (Akbarurrasyid et al., 2022; Ariadi et al., 2025; Chen et al., 2024; Iber & Kasan, 2021).

Water quality is a fundamental determinant of successful whiteleg shrimp farming. Suboptimal water conditions not only impair shrimp growth but also compromise immune function, increase susceptibility to infectious diseases, and, under severe conditions, trigger mass mortality, resulting in substantial economic losses (Iber & Kasan, 2021; Kumara et al., 2023; Ramadhan et al., 2024; Samsing & Barnes, 2024). Key physicochemical variables, including temperature, pH, salinity, dissolved oxygen (DO), and the concentrations of nitrogen- and phosphorus-containing compounds, directly regulate shrimp physiological performance while maintaining the ecological balance of pond ecosystems. Fluctuations in these parameters influence not only shrimp growth and survival but also reshape the composition and activity of microbial and planktonic communities that play essential roles in nutrient cycling within aquaculture ponds (Chen et al., 2024; Mustafa et al., 2022; Zhang et al., 2023).

Plankton, particularly phytoplankton, performs essential ecological functions in intensive aquaculture systems because the planktonic community collectively regulates biogeochemical nutrient cycling within pond ecosystems (Bagaskara et al., 2022; Qiao et al., 2020; Yang, Zhu, et al., 2020). In this context, phytoplankton serves as the primary producer, supplies dissolved oxygen through photosynthesis, assimilates nitrogen and phosphorus compounds, and contributes to the maintenance of water quality stability (Chen et al., 2024; Dokulil & Qian, 2021; Yang, Zheng, et al., 2020). The dominance of particular phytoplankton groups, such as Chlorophyta and diatoms, generally reflects a more stable aquatic environment than the dominance of Cyanophyta, which is frequently associated with deteriorating water quality and an increased risk of harmful algal blooms (Qiao et al., 2020; Yang, Zhu, et al., 2020). Consequently, plankton composition and abundance have been widely recognized as reliable biological indicators for assessing the ecological condition and environmental stability of aquaculture ponds (Nguyen et al., 2022).

The relationship between water quality and plankton dynamics is highly interactive because both components continuously influence one another throughout the production cycle. The decomposition of organic matter elevates nitrate and phosphate concentrations, thereby stimulating phytoplankton growth. In turn, shifts in plankton composition alter dissolved oxygen concentrations, pH, and nutrient availability within the pond ecosystem (Boyd et al., 2016; Kiswanto et al., 2026; Schrader et al., 2016). Appropriate water quality management practices, including mechanical aeration, periodic removal of accumulated organic sediments, and probiotic application, have been shown to maintain balanced microbial and plankton communities, thereby enhancing ecological stability and supporting the sustainability of intensive shrimp farming systems (Huang et al., 2022).

In general, previous studies have predominantly examined water quality, microbial communities, and plankton as separate research topics rather than as interconnected components of pond ecosystems. First, most available studies have evaluated either water quality parameters or plankton abundance independently, leaving the functional relationships between these two components insufficiently understood. Second, comprehensive investigations into the relationships between specific nutrient parameters, particularly nitrate and phosphate, and the composition and abundance of plankton communities in intensive pond systems remain limited, especially in Indonesia (Prates et al., 2024; Zhao et al., 2025). Third, plankton dynamics throughout the entire production cycle of intensive ponds, from pond preparation to harvest, have not been systematically documented (Kiswanto et al., 2026; Wang et al., 2026). Moreover, studies integrating water quality parameters with temporal variations in plankton abundance under commercial intensive farming conditions remain scarce, particularly in Indonesian whiteleg shrimp ponds. Such information is essential for improving our understanding of the biological responses of pond ecosystems to changing environmental conditions and for developing more effective, field-based strategies for water quality management (Kiswanto et al., 2026; Maulidhya et al., 2026; Mustafa et al., 2022).

Based on these considerations, this study aimed to evaluate water quality, quantify plankton abundance, and investigate the relationship between these two components in an intensive whiteleg shrimp (*Litopenaeus vannamei*) farming system at PT. Dua Putra Perkasa, Kaur Regency, Bengkulu, Indonesia. The findings are expected to provide a scientific basis for improving water quality management practices that maintain pond ecosystem stability and enhance the environmental sustainability of intensive whiteleg shrimp aquaculture.

RESEARCH METHODS

Study Site and Experimental Design

The study was conducted at the intensive whiteleg shrimp (*Litopenaeus vannamei*) farm operated by PT. Dua Putra Perkasa in Maje District, Kaur Regency, Bengkulu Province, Indonesia. Field observations were carried out over a two-month production period from September to December 2025. The study included seven lined intensive ponds, designated as Ponds 29–35, with pond areas ranging from 2,724 m² (Pond 29) to 6,618 m² (Pond 32).

The equipment used in this study was classified into two categories according to its intended application. Field measurements employed a pH meter equipped with an integrated temperature sensor, a digital dissolved oxygen (DO) meter, a salinity refractometer, a Secchi disk for water transparency measurements, and standard field recording sheets for daily data collection (Prates *et al.*, 2024). Laboratory analyses utilized a handheld refractometer, graduated cylinders, transparent glass bottles, BD syringes, sample bottles, titration-based test kits for alkalinity determination (HCO_3^- and CO_3^{2-}), colorimetric test kits for ammonium (NH_4^+), un-ionized ammonia (NH_3), nitrite (NO_2^-), nitrate (NO_3^-), and phosphate (PO_4^{3-}), as well as a light microscope for plankton observation and taxonomic identification (Al Karim et al., 2025; Sifa et al., 2026).

Water Quality Monitoring

Water quality data were obtained using complementary field and laboratory measurements. Daily in situ monitoring was conducted for pH and water temperature at 08:00 and 14:00, whereas water transparency was measured once daily at 14:00 when solar elevation provided consistent illumination for Secchi disk observations. Dissolved oxygen was measured every two days at 05:30 and 21:00. The early morning measurement represented the most critical period for dissolved oxygen because it followed a full night of organismal respiration in the absence of photosynthetic oxygen production.

Laboratory analyses were performed once each week at 09:00. The measured variables included salinity using a refractometer; NH_4^+ and NH_3 using colorimetric test kits; NO_2^- and NO_3^- using colorimetric test kits; PO_4^{3-} using a colorimetric test kit; and HCO_3^- and CO_3^{2-} using volumetric titration. Sampling at 09:00 was selected because the water column was generally well mixed at that time while remaining largely unaffected by the pronounced physicochemical fluctuations associated with midday solar heating and peak photosynthetic activity. Field and laboratory protocols followed standard operational procedures adapted from Corre et al. (2016), Baird et al. (2017), and Kiswanto et al. (2026).

Plankton Sampling and Enumeration

Plankton samples were collected once each week at 07:00 following the recommendations of Dokulil & Qian (2021), who indicated that plankton communities at this time provide a representative description of the pond ecosystem because photosynthetic activity has begun to stabilize after sunrise. At each sampling event, a known volume of pond water (Vs) was filtered through a plankton net and concentrated to a filtrate volume (Vr) of 50 mL, from which a 1 mL subsample (Vo) was examined under a light microscope. Cells were identified to genus level using standard phytoplankton identification references (Baird et al., 2017) and classified into four major groups: green algae (Chlorophyta, GA), blue-green algae (Cyanobacteria, BGA), diatoms (Bacillariophyta, DIATOM), and dinoflagellates (Dinophyta, DINO). Zooplankton were not assessed in this study; the term plankton in the title reflects the community sampled, which in this study comprised phytoplankton only. Phytoplankton abundance (N, cells L^{-1}) was calculated as:

$$N = n\,x\,(\frac{Vr}{Vo})\,\mathrm{x}\,(\frac{1}{Vs}) \quad (1)$$

where *N* represents plankton abundance, *n* is the number of plankton individuals counted in the observation chamber, *Vr* is the concentrated sample volume (50 mL), *Vo* is the observed volume (1 mL), and *Vs* is the volume of pond water filtered during sample collection, which varied among ponds according to field conditions (Arifin et al., 2018; Satyawan et al., 2024).

Data Analysis

The collected data were analyzed using a descriptive–quantitative approach that integrated numerical observations with contextual ecological interpretation. The mean and range (minimum–maximum) were calculated for each water quality parameter in every pond. Plankton community composition was expressed as the relative proportion of the major taxonomic groups, including Green Algae (GA), Blue-Green Algae (BGA), Diatoms (DIATOM), and Dinoflagellates (DINO), based on total plankton abundance. Relationships between water quality parameters and plankton abundance were interpreted using established ecological mechanisms.

RESULTS AND DISCUSSION

The discussion follows a conceptual pathway in which feed-derived organic waste releases ammonium (NH_4^+), which is converted through nitrification into nitrate (NO_3^-) and assimilated by phytoplankton. The resulting photosynthetic activity may increase dissolved oxygen, stabilize water quality, and support shrimpt growth. Accordingly, the results and discussion are organized into the following subsections.

General Water Quality Conditions and Plankton Community Structure as Indicators of Ecosystem Stability in Intensive Aquaculture

The results showed that most water quality parameters remained within conditions that supported intensive *Litopenaeus vannamei* culture throughout the 72-day rearing period. The pH (7.5–8.2), temperature (26.9–31.5°C), salinity (30–34 ppt), water transparency (30–40 cm), and mean DO concentration of 4.6 mg/L indicated environmental conditions that were generally capable of supporting shrimp physiological balance and pond biogeochemical processes (Table 1). However, increases in NH_4^+ and NO_2^- during several periods indicated the onset of nutrient pressure associated with high feed inputs, shrimp metabolism, and organic matter accumulation. These conditions indicate that pond stability depends not only on physicochemical parameters but also on the biological capacity of the ecosystem to assimilate and transform nutrients. Hu et al. (2026) reported that feed input is a major source of nitrogen in shrimp aquaculture systems and can subsequently contribute to the accumulation of ammonia, nitrite, and nitrate. Chen et al. (2024) similarly stated that feed input is a major nitrogen source in shrimp aquaculture systems and may consequently lead to the accumulation of ammonia, nitrite, and nitrate.

The plankton findings further support this interpretation. Total plankton abundance ranged from 204,000 to 440,000 cells/L and was dominated by Chlorophyta, particularly *Chlorella* and *Tetraselmis*, while diatoms such as *Navicula, Nitzschia, Chaetoceros,* and *Bellerochea* remained present at lower abundances (Table 2). The dominance of these photosynthetic microalgae indicates that primary productivity and nutrient utilization remained relatively effective. *Chlorella* and *Tetraselmis* contribute to nitrogen and phosphorus uptake, oxygen production, and biomass formation that supports energy flow within the pond ecosystem. Conversely, the low abundance of Cyanophyta and Dinoflagellata supports the interpretation that no potentially problematic group had become dominant, although these groups alone are insufficient as single indicators of eutrophication. Khatoon et al. (2021) reported that *Tetraselmis* sp. can reduce total ammonia nitrogen (TAN), nitrite nitrogen, and dissolved phosphorus in aquaculture wastewater. Gao et al. (2018) and Soeprapto et al. (2023) also reported that *Chlorella* can assimilate nutrients while producing algal biomass. Campos et al. (2021) further reported that Cyanophyta can become dominant in shrimp ponds and that Cyanophyta abundance is positively correlated with orthophosphate.

Table 2. Water quality parameters recorded in seven intensive *Litopenaeus vannamei* culture ponds at PT Dua Putra Perkasa during the 72-day observation period

Parameter	Unit	Range
Temperature	°C	26.9–31.5
Water clarity	cm	30–40
pH	–	7.5–8.2
Dissolved oxygen (DO)	mg/L	4.2–5.0
Salinity	ppt	30–34
Total ammonia (NH_4^+)	mg/L	1.00–7.00
Free ammonia (NH_3)	mg/L	0.01–0.20
Nitrite (NO_2^-)	mg/L	0.50–3.75
Nitrate (NO_3^-)	mg/L	5–38
Phosphate (PO_4^{3-})	mg/L	0.50–2.50
Carbonate (CO_3^{2-})	mg/L	5–10

Ecologically, these conditions indicate that the ponds remained in a state of dynamic equilibrium. Nevertheless, the occasional increases in NH_4^+ and NO_2^- indicate that the assimilative capacity of the system was beginning to experience pressure. Therefore, nutrient inputs, organic matter, and plankton communities should be managed in an integrated manner to maintain water quality, support shrimp physiology, and prevent ecological instability during intensive culture.

Table 2. Phytoplankton abundance and relative composition in seven intensive *Litopenaeus vannamei* ponds at PT Dua Putra Perkasa

Pond	Dominant genera	GA (cells/L)	BGA (cells/L)	DIATOM (cells/L)	DINO (cells/L)	Total (cells/L)	GA (%)	BGA (%)	DIATOM (%)	DINO (%)
29	*Chlorella, Tetraselmis, Navicula, Nitzschia*	233,990	0	50,887	17,123	302,000	77.48	0.00	16.85	5.67
30	*Chlorella, Tetraselmis, Navicula, Oscillatoria*	286,002	1,746	47,194	11,058	346,000	82.66	0.50	13.64	3.20
31	*Chlorella, Tetraselmis, Nitzschia, Navicula*	260,007	0	42,603	27,390	330,000	78.79	0.00	12.91	8.30
32	*Chlorella, Tetraselmis, Nitzschia, Chaetoceros*	190,005	0	7,222	6,773	204,000	93.14	0.00	3.54	3.32
33	*Chlorella, Nitzschia, Tetraselmis, Chaetoceros*	216,000	0	8,326	5,674	230,000	93.91	0.00	3.62	2.47
34	*Chlorella, Tetraselmis, Nitzschia, Navicula*	204,975	0	48,770	14,255	268,000	76.48	0.00	18.20	5.32
35	*Chlorella, Tetraselmis, Nitzschia, Bellerochea*	369,996	0	32,252	37,752	440,000	84.09	0.00	7.33	8.58

GA = Green Algae (Chlorophyta); BGA = Blue-Green Algae (Cyanobacteria); DIATOM = Bacillariophyta; DINO = Dinoflagellata. Percentages were recalculated from the raw cell counts reported in this table and are internally consistent with total abundance values.

Interactions among Physicochemical Water Quality Parameters in Regulating Ecosystem Stability in Intensive *Litopenaeus vannamei* Aquaculture

The stability of an intensive *Litopenaeus vannamei* aquaculture ecosystem results from interactions among temperature, DO, pH, salinity, water transparency, the carbonate system, and biological activity. The temperature range observed in this study remained within the tolerance range of *Litopenaeus vannamei* (Table 1), thereby supporting metabolism, osmoregulation, growth, and immune responses while also facilitating photosynthesis, organic matter decomposition, and nitrification (Abdelrahman et al., 2019; Ren et al., 2021). Although increasing temperature can reduce oxygen solubility and increase metabolic demand, the consistently adequate DO concentration indicates that aeration and oxygen production by phytoplankton were sufficient to compensate for oxygen consumption by organisms within the ponds.

The stability of pH (Table 1) also indicates that photosynthesis and respiration remained relatively balanced. This condition is important because pH and temperature jointly determine the proportion of NH_3, which is more toxic than NH_4^+. Therefore, an increase in inorganic nitrogen does not automatically indicate toxic conditions when other controlling factors remain favorable. Alfiansah et al. (2018) reported that pH, DO, ammonium, and nitrite concentrations in their study system remained well below lethal levels for shrimp. Valencia-Castañeda et al. (2019), using juvenile *L. vannamei* directly to assess the toxicity of ammonia, nitrite, and nitrate, also found that increases in inorganic nitrogen do not automatically indicate toxicity because the concentration and chemical form of nitrogen determine the associated toxic risk.

Relatively stable water transparency also helped maintain light penetration and primary productivity, whereas relatively constant salinity supported shrimp osmoregulation and maintained a phytoplankton community adapted to high-salinity conditions. Lestariaji et al. (2026) reported that reductions in total suspended solids (TSS) increase light penetration and thereby support phytoplankton photosynthesis. In a study conducted on *Penaeus vannamei* ponds across a salinity gradient, Li et al. (2025) also reported that suitable salinity conditions can support a more balanced plankton community and shrimp growth. Adequate carbonate buffering capacity further contributes to pH stability and supports nitrification, thereby facilitating nitrogen transformation. These conditions are consistent with the dominance of *Chlorella* and *Tetraselmis*, which reflects a productive and relatively stable environment (Boyd et al., 2016; Do et al., 2026). Ecologically, these parameters interact to create a dynamic balance that supports primary productivity, nutrient transformation, and shrimp physiological condition. Nevertheless, increasing organic loading during culture may shift this balance. Therefore, water quality management should integrate the interactions among parameters and plankton community responses rather than rely on a single indicator.

Nitrogen and Phosphorus Cycling as Drivers of Plankton Community Structure in Intensive *Litopenaeus vannamei* Aquaculture

Intensive *Litopenaeus vannamei* culture receives substantial nitrogen and phosphorus inputs through feed, excretion, and the decomposition of organic residues. Some of these nutrients undergo mineralization to NH_4^+. Therefore, increases in NH_4^+ during culture are more appropriately interpreted as part of nutrient recycling rather than solely as an indicator of declining water quality (Chaikaew et al., 2019; Chen et al., 2024). Ecological risks arise when NH_4^+ production exceeds the capacity of microorganisms and phytoplankton to assimilate it. In the present study, NH_4^+ occasionally increased, but NH_3 remained relatively low because pH and temperature were relatively stable. Thus, no serious trend in direct toxic pressure on shrimp was observed, although the increase in nitrogen still requires attention.

A portion of NH_4^+ subsequently undergoes nitrification to NO_2^- and NO_3^-. Adequate DO and bicarbonate concentrations allow this process to proceed, but the increase in NO_2^- during some observations indicates that nitrite oxidation did not fully compensate for NH_4^+ production. This condition reflects increasing nitrogen pressure associated with the growing organic load. For shrimp, nitrite accumulation requires attention because prolonged exposure can interfere with oxygen transport and increase physiological stress. Chen et al. (2024) reported that, in shrimp aquaculture systems, feed is a major nitrogen source that generates nitrogenous wastes in the sequence $NH_3/NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$. These transformations involve various functional microbial groups and represent an important component of nitrogen cycling that contributes to nitrogen waste removal and the maintenance of aquaculture system stability. Conversely, the occurrence of NO_3^- within a relatively suitable range indicates that part of the nitrogen had been transformed into a more stable form that can be reused by primary producers. Conceptually, the nitrogen cycle in shrimp aquaculture can be described as follows: nitrogen derived from feed and culture waste undergoes the sequence organic N $\rightarrow NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$. Nitrification converts more reduced forms of nitrogen into more oxidized forms. Nitrate then becomes part of the nitrogen pool that can be assimilated by autotrophic organisms or undergo further microbial transformations (Chen et al., 2024).

Phosphate also plays an important role in maintaining primary productivity. Its relatively low concentration suggests that some phosphorus was rapidly assimilated by phytoplankton. This pattern is consistent with the dominance of *Chlorella* and *Tetraselmis*, which can rapidly utilize nitrogen and phosphorus for biomass production (Chen et al., 2024). Overall, this pattern indicates that the plankton community continued to function as a biological nutrient regulator, converting part of the nitrogen and phosphorus waste into primary biomass and thereby limiting its immediate accumulation as a pollutant load. However, this balance remains dynamic. When nutrient inputs exceed the assimilative capacity of the system, nitrogen and phosphorus accumulation may shift the community toward Cyanophyta or other opportunistic groups and increase the risk of water quality instability. Therefore, nutrient cycling efficiency and plankton community responses should form the basis of intensive aquaculture management rather than relying solely on the control of individual nutrient concentrations.

Phytoplankton Community Structure as an Indicator of Ecological Stability in *Litopenaeus vannamei* Ponds

The phytoplankton community structure observed in this study showed a relatively consistent biological response to pond environmental conditions. Chlorophyta, particularly *Chlorella* and *Tetraselmis*, dominated the community, accompanied by diatoms such as *Navicula, Nitzschia, Chaetoceros,* and *Bellerochea*, whereas Cyanophyta and Dinoflagellata remained at low abundances. This pattern indicates that the ecosystem was able to maintain primary productivity without showing a shift toward potentially problematic opportunistic groups that could impair water quality. Therefore, plankton composition provides an integrated picture of ecological stability that cannot be fully captured by instantaneous physicochemical measurements alone (Inayah et al., 2023; Lyu et al., 2021).

The dominance of *Chlorella* and *Tetraselmis* is ecologically important in intensive aquaculture systems because these microalgae can effectively utilize nitrogen and phosphorus while maintaining photosynthetic activity (Khatoon et al., 2021; Sacristán de Alva & Luna Pabello, 2021). Their ability to directly assimilate NH_4^+ allows part of the nitrogen released through decomposition to be rapidly converted into biomass, thereby reducing the potential accumulation of nutrients in the water column. At the same time, oxygen production through photosynthesis supports aerobic conditions required for shrimp respiration and microbial activity. The presence of diatoms further contributes to primary productivity and provides important nutritional components for the pond food web. Khatoon et al. (2021) reported that, in a study using aquaculture wastewater, including shrimp pond wastewater, *Tetraselmis* directly reduced nitrogen and phosphorus compounds, achieving approximately 98.9% reduction in total ammonia nitrogen (TAN), 97.7% reduction in nitrite-N, and 91.1% reduction in soluble reactive phosphorus within 48 hours.

Conversely, the low abundance of Cyanophyta and Dinoflagellata indicates that environmental conditions had not favored the dominance of groups that commonly proliferate under nutrient imbalance or ecological stress (Campos et al., 2021; Lyu et al., 2021; Munawar & Fitzpatrick, 2018). The dominance of Chlorophyta may also contribute to stability through rapid competition for available nutrients. Overall, the phytoplankton community structure indicates that the ponds retained relatively good ecological resilience to nutrient loading during the culture period. This condition is beneficial to shrimp because primary productivity, oxygen availability, and nutrient transformation could proceed in a relatively balanced manner. Nevertheless, this balance remains dynamic. An increase in organic loading or deterioration of water quality beyond the assimilative capacity of the plankton community may alter community structure and increase the risk of ecosystem instability.

Integrating Water Quality and Plankton Community Dynamics as Mechanisms Regulating Ecosystem Stability in Intensive *Litopenaeus vannamei* Aquaculture

The stability of an intensive *Litopenaeus vannamei* aquaculture ecosystem results from interactions among physical, chemical, and biological factors rather than from the response of any single parameter. High feed input increases production but also increases the organic load through uneaten feed and shrimp excretion. The resulting organic matter is decomposed to NH_4^+, which is partly assimilated by phytoplankton and partly transformed through nitrification into NO_2^- and NO_3^-. Therefore, an increase in nutrient concentrations does not necessarily represent immediate pollution because nutrients can still be regulated through biological processes (Chen et al., 2024; Jescovitch et al., 2018).

The dominance of *Chlorella* and *Tetraselmis* indicates that nutrient assimilation remained effective. These microalgae utilize nitrogen and phosphorus for biomass production while releasing oxygen through photosynthesis. This oxygen supports shrimp respiration and nitrifying bacterial activity, thereby facilitating nitrogen transformation and helping to prevent the accumulation of toxic nitrogen compounds (Khatoon et al., 2021; Nasir et al., 2023). Conversely, declining phytoplankton productivity may disrupt this balance because limited oxygen availability can inhibit nitrification and increase NH_4^+ and NO_2^- accumulation (de Morais et al., 2020).

The carbonate system also contributes to maintaining equilibrium through the capacity of bicarbonate to buffer pH changes associated with photosynthesis and respiration. Relatively stable pH conditions also limit increases in the fraction of NH_3, which is more toxic to shrimp. At the community level, the presence of diatoms such as *Navicula, Nitzschia, Chaetoceros,* and *Bellerochea* broadens the capacity for nutrient utilization, whereas the low abundance of Cyanophyta indicates that ecological pressure had not yet favored the dominance of opportunistic groups (Geng et al., 2020; Huang et al., 2022; Zhang et al., 2023).

Overall, the ponds exhibited relatively good ecological resilience, although the occasional increases in NH_4^+ and NO_2^- indicate that the safety margin was beginning to narrow. This condition provides an early warning that sustained increases in nutrient loading could exceed the assimilative capacity of the system. Therefore, feed management, aeration optimization, organic matter management, and plankton monitoring should be integrated to maintain water quality, support shrimp physiology, and prevent the ecosystem from shifting toward an unstable state.

Variation among Ponds in Plankton Community Structure and Its Implications for Aquaculture Ecosystem Dynamics

Although all ponds were managed under the same intensive culture system, the plankton community structure showed differences in abundance among ponds. These differences more likely reflect the internal dynamics of individual culture units than differences in management quality because all ponds remained dominated by *Chlorella* and *Tetraselmis*, accompanied by diatoms in varying proportions, while Cyanophyta and Dinoflagellata remained low. This consistency indicates that the basic ecological conditions were relatively homogeneous, whereas differences in abundance reflected variations in productivity and nutrient utilization at the pond scale. Akbarurrasyid et al. (2022) reported that three intensive ponds of similar size and managed under the same treatment conditions exhibited differences in plankton abundance and diversity among ponds.

P35 had the highest total plankton abundance, approximately 440,000 cells/L, and was dominated by *Chlorella, Tetraselmis, Nitzschia,* and *Bellerochea*. The high phytoplankton biomass, together with a relatively stable community composition, indicates increased primary productivity without evidence of a shift toward opportunistic groups. The presence of *Bellerochea* may also indicate microhabitat variation, potentially associated with nutrient distribution, water mixing, or silicate availability. In contrast, P32 had the lowest abundance, approximately 204,000 cells/L, but retained a similar dominant community composition. This pattern suggests that the quantitative differences more likely reflected variations in productivity than ecological disturbance. This interpretation is consistent with Akbarurrasyid et al. (2022), who reported that three intensively managed ponds with identical culture treatments but no different experimental variables nevertheless exhibited differences in plankton abundance. These findings indicate that the observed variation was more closely associated with internal conditions and water quality within individual ponds.

Differences among ponds may be influenced by organic matter accumulation, nutrient distribution from feed, aeration efficiency, and grazing pressure. The occurrence of *Oscillatoria* only in P30 at very low abundance indicates a localized response to microhabitat conditions but does not, by itself, indicate eutrophication. Likewise, Dinoflagellata remained a minor component across all ponds, whereas diatoms were consistently present despite differences in their relative contributions. This pattern is important because substantial environmental deterioration may be accompanied by shifts in dominant groups rather than changes in abundance alone. Munjayana et al. (2024) reported that, across six intensive *L. vannamei* ponds monitored for 98 days, plankton composition, total organic matter (TOM), and salinity were associated with plankton abundance. TOM tended to increase during culture but remained within a range tolerated by shrimp.

Therefore, total plankton abundance should not be interpreted as a stand-alone indicator of water quality. Community structure provides more informative evidence for evaluating ecological function. Overall, the consistent dominance of Chlorophyta, the presence of diatoms, and the low abundance of Cyanophyta and Dinoflagellata indicate that all ponds remained within a relatively resilient ecological state, whereas differences in abundance primarily reflected variation in primary productivity among ponds.

Conceptual Synthesis and Scientific Contribution of the Study to the Development of *Litopenaeus vannamei* Aquaculture Ecosystem Management

The results demonstrate that the stability of intensive *Litopenaeus vannamei* culture is a consequence of interactions among physicochemical conditions, microbial activity, and plankton community structure. Parameters such as temperature, pH, salinity, DO, inorganic nitrogen, and phosphate provide information on environmental conditions but do not fully explain the ecological processes occurring within the system. Integrating these parameters with phytoplankton community structure provides a more comprehensive perspective because the community represents a biological response to environmental changes while simultaneously contributing to nutrient cycling.

Feed, as a major source of nitrogen and phosphorus, enters the biogeochemical cycle through excretion, decomposition, mineralization, and nitrification (Chen et al., 2024; Jescovitch et al., 2018). Some of these nutrients are subsequently assimilated by phytoplankton and therefore do not all accumulate as pollutant loads. The dominance of *Chlorella* and *Tetraselmis*, together with the presence of *Navicula, Nitzschia, Chaetoceros,* and *Bellerochea*, indicates that biological assimilative capacity remained sufficient to offset nutrient inputs. Photosynthetic activity by these groups also supports oxygen availability and the aerobic conditions required for nitrogen transformation. Conversely, the low abundance of Cyanophyta and Dinoflagellata indicates that nutrient pressure had not yet driven a shift in community structure toward opportunistic groups.

These findings indicate that ecosystem stability is not defined solely by low nutrient concentrations but by the ability of the system to transform and utilize nutrients effectively. Phytoplankton community structure therefore has both diagnostic and functional value for assessing pond resilience. Differences in plankton abundance among ponds without changes in the dominant groups further indicate that productivity fluctuations had not yet caused major disruption to basic ecological functions. Lyu et al. (2021) similarly reported that phytoplankton community dynamics can serve as a metric of environmental quality in intensive aquaculture, particularly under healthy conditions characterized by greater community stability.

Conceptually, this study supports a model in which aquaculture performance is determined by the balance among three components: physicochemical conditions as environmental regulators, microorganisms as drivers of nutrient transformation, and phytoplankton as regulators of productivity and a biological nutrient buffer. This integrative approach can provide a basis for more adaptive, preventive, and sustainable water quality monitoring to maintain productivity while preserving the biological health of *L. vannamei*.

CONCLUSION

The results showed that water quality conditions in the intensive *Litopenaeus vannamei* culture system at PT Dua Putra Perkasa, Kaur Regency, Bengkulu, generally remained supportive of culture throughout the 72-day rearing cycle. Temperature (26.9–31.5°C), pH (7.5–8.2), salinity (30–34 ppt), water transparency (30–40 cm), and dissolved oxygen (mean 4.6 mg/L) were generally sufficient to support shrimp physiological processes and pond biogeochemical activity. However, the increases in NH_4^+ and NO_2^- observed during several periods indicate that nutrient pressure increased with culture intensity.

Plankton abundance ranged from 204,000 to 440,000 cells/L and was dominated by Chlorophyta, particularly *Chlorella* and *Tetraselmis*, accompanied by diatoms such as *Navicula, Nitzschia, Chaetoceros,* and *Bellerochea*. In contrast, Cyanophyta and Dinoflagellata occurred at low proportions. This community structure indicates that primary productivity and nutrient assimilation remained relatively effective and that no shift toward opportunistic groups was observed.

Ecologically, water quality and plankton community structure were closely interconnected. Nutrient availability supported phytoplankton growth, whereas photosynthetic activity and nutrient assimilation contributed to oxygen availability, carbon balance, and nitrogen transformation. Therefore, pond stability is determined not only by the individual values of water quality parameters but also by the ability of the ecosystem to maintain a balance among nutrient inputs, biogeochemical transformation, and nutrient utilization by the plankton community. Integrating water quality monitoring with plankton community structure is important for maintaining productivity and supporting the sustainability of intensive *L. vannamei* aquaculture.

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