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RELATIONSHIPS BETWEEN PRIMARY WATER QUALITY PARAMETERS AND CYANOPHYTA ABUNDANCE IN INTENSIVE WHITELEG SHRIMP (*Litopenaeus vannamei*) PONDS

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ABSTRACT

Phytoplankton dynamics, especially Cyanophyta abundance, play a crucial role in shaping water quality and overall productivity in intensive whiteleg shrimp (*Litopenaeus vannamei*) culture. However, the interactions between key water quality parameters and Cyanophyta proliferation remain poorly understood under commercial farming conditions. This study aimed to examine the relationships between ammonium, nitrite, nitrate, phosphate, total organic matter (TOM), dissolved oxygen (DO), and Cyanophyta abundance in two intensive shrimp ponds with contrasting phytoplankton conditions. This study compared two ponds operated by PT Pyramide Paramount Indonesia that differed in stocking density, pond size, and culture conditions. Weekly measurements included Cyanophyta abundance and composition using microscopy and a Neubauer counting chamber, as well as monitoring water quality parameters daily and weekly through *in-situ* and *ex-situ* methods. Pearson's correlation was used to assess the relationships between the variables. The High Cyanophyte (HC) pond exhibited significantly higher cell abundance (47,400 cells mL^{-1}) and dominance compared to the Low Cyanophyte (LC) pond (18,250 cells mL^{-1}). Multiple regression confirmed that dissolved oxygen was the only significant predictor of Cyanophyta abundance, explaining 51.9% of the variance, whereas nutrients and total organic matter were not significant predictors. Shrimp in the LC pond showed better growth performance, with higher final biomass (6,110.33 kg), lower FCR (1.26), and greater productivity (17.65 ton ha^{-1}), indicating that lower Cyanophyta levels may promote more stable culture conditions than higher ones. These findings highlight the need to manage phytoplankton dynamics and DO availability to enhance water quality and promote sustainable shrimp farming.

KEYWORDS: cyanophyta; dissolved oxygen; *Litopenaeus vannamei*; **phytoplankton; shrimp farming; water quality**

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ABSTRAK: Hubungan antara Parameter Kualitas Air Primer dan Kelimpahan Cyanophyta pada Tambak Intensif Udang Vaname (*Litopenaeus vannamei***)**

*Dinamika fitoplankton, khususnya kelimpahan Cyanophyta, berperan penting dalam membentuk kualitas air dan produktivitas secara keseluruhan pada budidaya intensif udang vaname (***Litopenaeus vannamei***). Namun, interaksi antara parameter kualitas air utama dan proliferasi Cyanophyta masih kurang dipahami dalam kondisi budidaya komersial. Penelitian ini bertujuan untuk mengkaji hubungan antara amonium, nitrit, nitrat, fosfat, total bahan organik (TOM), oksigen terlarut (DO), dan kelimpahan Cyanophyta di dua tambak udang intensif dengan kondisi fitoplankton yang kontras. Penelitian ini membandingkan dua tambak yang dioperasikan oleh PT Pyramide Paramount Indonesia, namun berbeda dalam kepadatan tebar, ukuran tambak, dan kondisi budidaya. Pengukuran mingguan meliputi kelimpahan dan komposisi Cyanophyta menggunakan mikroskop dan counting chamber Neubauer, sementara parameter kualitas air dipantau secara harian dan mingguan melalui metode in-situ dan ex-situ. Korelasi Pearson digunakan untuk menilai hubungan antarvariabel. Tambak dengan kelimpahan Cyanophyta tinggi (HC) menunjukkan kelimpahan sel yang jauh lebih tinggi (47.400 sel mL^{-1}) dan dominansi dibandingkan dengan kolam kelimpahan Cyanophyta rendah (LC) (18.250 sel mL^{-1}). Analisis regresi berganda mengonfirmasi oksigen terlarut sebagai satu-satunya prediktor signifikan bagi kelimpahan Cyanophyta, yang menjelaskan 51.9% varians, sementara nutrien dan total bahan organik bukan merupakan prediktor yang signifikan. Udang di tambak LC menunjukkan kinerja pertumbuhan yang lebih baik, dengan biomassa akhir lebih tinggi (6,110.33 kg), FCR lebih rendah (1.26), dan produktivitas lebih besar (17.65 ton ha^{-1}), yang mengindikasikan bahwa tingkat Cyanophyta yang lebih rendah dapat mendukung kondisi budidaya yang lebih stabil. Temuan ini menekankan pentingnya pengelolaan dinamika fitoplankton dan ketersediaan oksigen terlarut untuk meningkatkan kualitas air dan produksi udang yang berkelanjutan.*

KATA KUNCI: ***budidaya udang; cyanophyta; fitoplankton; kualitas air;*** *Litopenaeus vannamei;* ***oksigen terlarut***

INTRODUCTION

As one of the important components of aquaculture, intensive farming of whiteleg shrimp (*Litopenaeus vannamei*) has expanded rapidly in meeting the growing global seafood demand (Dugassa & Gaetan, 2018; Mustafa *et al*., 2024). These intensive systems are characterized by high stocking densities and substantial feed inputs, which, while boosting productivity, can lead to rapid nutrient accumulation and the subsequent deterioration of water quality (Ritonga, 2021). The sustainability and profitability of such systems depend on a stable environment.

In intensive aquaculture ponds, the concentrations of specific nutrients, including ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and phosphate (PO_4^{3-}), are of critical importance. These compounds originate largely from uneaten feed, shrimp excretion, and the accumulation of organic waste (Han *et al*., 2017; Wasielesky *et al*., 2016). While essential for primary production, excess nutrients can trigger eutrophication, stimulating the proliferation of phytoplankton, including Cyanophyta (blue-green algae) (Musa *et al*., 2023). Although a balanced phytoplankton community is beneficial for oxygen production and nutrient cycling, the overgrowth of Cyanophyta can lead to harmful algal blooms (HABs), which pose multifaceted threats to shrimp aquaculture (Gao *et al*., 2017; Sultana *et al*., 2022). In addition to oxygen depletion during night time respiration and bloom decay, certain Cyanophyta genera, particularly *Microcystis*, *Anabaena*, and *Oscillatoria*, produce potent hepatotoxins (microcystins) and neurotoxins that can accumulate in shrimp tissues, causing histological damage to the hepatopancreas and gills, impairing immune function, and increasing susceptibility to diseases (Gao *et al*., 2017; Rastogi *et al*., 2015). Furthermore, filamentous Cyanophyta, such as *Oscillatoria,* can form surface scums that reduce light penetration, while their decay produces taste-and-odor compounds that taint shrimp flesh, compromising product quality and market value (Ariadi *et al*., 2019; Sultana *et al*., 2022). These cumulative effects threaten shrimp health and survival, which in turn undermine production stability and economic returns, making Cyanophyta management a critical priority for sustainable shrimp farming.

Dissolved oxygen (DO) is a master variable that is integrally linked to the nitrogen and phosphorus cycles in aquatic ecosystems. Adequate DO levels are essential for the nitrification, the biological conversion of toxic ammonium to nitrite and then to less harmful nitrate (Chen *et al*., 2024). Under hypoxic conditions, this process is inhibited, leading to the accumulation of ammonium and nitrite, which are directly toxic to penaeid shrimp, even at low concentrations (Han *et al*., 2017). Similarly, aerobic microbial activity facilitates the mineralization of organic phosphorus to bioavailable phosphate (Yuan *et al*., 2024), a process that can be compromised at low DO levels.

Oxygen dynamics in a pond are profoundly influenced by the total organic matter (TOM) load (McCabe *et al*., 2021). High TOM, derived from residual feed and fecal matter, fuels microbial decomposition, a process that consumes large quantities of oxygen (Nindarwi *et al*., 2025). This process can create hypoxic or anoxic zones, especially in the benthic layer, promoting the release of nutrients from sediments and the growth of anaerobic bacteria that produce toxic substances, such as hydrogen sulfide (D'Aoust *et al*., 2018). This condition creates a feedback loop; for example, the decomposition of cyanobacterial blooms creates microenvironments with low DO and reductive conditions that promote substantial release of nitrogen and phosphorus into the water column, making these nutrients available to fuel further phytoplankton growth (Yan *et al*., 2017).

While previous research has elucidated the individual effects of nutrients or DO on aquaculture systems, a comprehensive understanding of their integrated impacts under commercial conditions remains limited. However, laboratory-based research, while valuable for controlled testing, often lacks the ecological complexity required to represent operational pond conditions (Gabrielyan et al., 2023; Nguyen *et al*., 2025). Field investigations have typically focused on specific aspects, such as nutrient thresholds (Burford *et al*., 2023), single-factor relationships (Delgado *et al*., 2024), or particular management interventions, creating a fragmented knowledge base. This condition leaves a critical gap in understanding how DO, TOM, and the complete nutrient spectrum (NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-}) interact synergistically to drive the dynamics of Cyanophyta in intensive shrimp ponds operating under real-world constraints. Such integrated analyses are essential for developing predictive models and targeted management strategies that address the root causes of Cyanophyta proliferation rather than treating symptoms in isolation.

This study investigated how variations in key water quality parameters, specifically ammonium, nitrite, nitrate, phosphate, total organic matter, and dissolved oxygen, influence the abundance of Cyanophyta in *Litopenaeus vannamei* intensive farming ponds. We hypothesized that dissolved oxygen would demonstrate the strongest association with Cyanophyta dynamics, whereas individual nutrient concentrations would show weaker relationships in these complex aquaculture systems. By employing a comparative observational approach combined with both correlation and multiple regression analyses, this study sought to identify the key drivers of Cyanophyta blooms. The findings are expected to provide practical insights for optimizing water quality management strategies, such as aeration, nutrient control, and organic load reduction, to prevent harmful algal blooms and promote sustainable and efficient shrimp farming practices.

MATERIALS AND METHODS

Time and Place

This study was conducted at two intensive whiteleg shrimp ponds owned and operated by PT Pyramide Paramount Indonesia. Two ponds were selected for sampling to represent varying levels of cyanophyte abudance, designated as High Cyanophyte (HC) and Low Cyanophyte (LC). Data were collected from August to November 2024.

Research Materials

This study used various materials and instruments to monitor and analyze water quality and Cyanophyta abundance. Water samples were collected using 1-L darkened HDPE (high density polyethylene) bottles and preserved with Lugol's iodine solution (Lugol's Iodine S019, HiMedia Laboratories Pvt. Ltd., Thane West Maharashtra, India) to maintain phytoplankton integrity for microscopic observation. Cyanophyta enumeration and identification were performed using a binocular microscope (Olympus, Japan) at 40× magnification in combination with a Neubauer counting chamber (Marienfeld Superior, Paul Marienfeld GmbH & Co. KG, Lauda-Königshofen, Germany).

Daily *in-situ* measurements of dissolved oxygen, temperature, and salinity were conducted using a multiparameter probe (YSI Pro20, YSI Inc., Yellow Springs, USA), and pH was measured using a calibrated digital pH meter (EZ-9909, Thincol, USA). For weekly *ex-situ* water quality assessments, the concentrations of ammonium, nitrite, nitrate, and phosphate were determined using colorimetric test kits (Ammonium Test 108024, Nitrite Test 108025, Nitrate Test 111170, and Phosphate Test 114846; all from Merck KGaA, Darmstadt, Germany). Microbiological evaluation of total *Vibrio* counts was performed by culturing samples on thiosulfate citrate bile salts sucrose (TCBS) agar (BD Difco™ TCBS Agar, Becton, Dickinson and Company, USA), followed by incubation and colony enumeration.

Research Design

This study followed a comparative observational approach to investigate the relationships between water quality parameters and Cyanophyta abundance in two intensive whiteleg shrimp ponds. Pond selection was carried out using a purposive sampling method based on specific criteria presented in Table 1, including ponds that used shrimp from the same hatchery but differed in stocking time, pond size, and stocking density. These controlled variations represent the actual operational conditions of shrimp farming in Indonesia. This variation allows for meaningful comparisons of environmental conditions and phytoplankton responses in intensive shrimp ponds.

Although both ponds were managed under the same farm management and followed standard operating procedures (SOPs) for feeding, aeration, and monitoring, natural pond dynamics and operational schedules led to distinct ecological characteristics. After the completion of the grow-out period of 83 days for the C3 pond and 81 days for the D2 pond, the abundance of Cyanophyta was analyzed using routine phytoplankton data collected during the grow-out period. Based on this assessment, the ponds were classified into two types: D2 with low Cyanophyta abundance (LC) and C3 with high Cyanophyta abundance (HC).

Work Procedure

Pond and Feeding Management

The ponds were prepared and managed in accordance with the operational standards set by PT Pyramide Paramount Indonesia, Farm Goris, Buleleng, Bali, Indonesia. Prior to stocking, each pond underwent a drying period of 10–14 days to improve bottom conditions and reduce the presence of pathogens. This activity was followed by mechanical cleaning using high-pressure water and brushes to remove accumulated algae, sludge, and other biofouling organisms. All HDPE liners and operational equipment, including paddlewheels and sampling bridges, were carefully inspected and repaired before the ponds were refilled.

Water was sourced from a main reservoir, pre-treated in sedimentation tanks, and then transferred into the ponds to a final depth of 120 cm. A sterilization protocol was applied to the grow-out ponds, involving sequential treatment with iodine (Iodine Providone Aquaculture, CV. Mitra Niaga Pumpindo, Indonesia) at 1 ppm and hydrogen peroxide (H_2O_2) (produced by PT Evonik Indonesia, Indonesia) at 10 ppm. After sterilization, a commercial probiotic containing *Lactobacillus plantarum*, *Bacillus subtilis* and *Saccharomyces cerevisiae* (Super Lacto, PT CPP, Indonesia) was introduced at 1 ppm and activated with 2 ppm molasses to promote the development of beneficial microbial communities. To further support early ecosystem balance, dolomite (Dolomite Super, PT Cipta Makmur Jaya, Indonesia) and fermented rice bran (locally supplied materials), along with a commercial probiotic (Super Lacto, PT CPP, Indonesia), were regularly applied to promote phytoplankton growth and enhance overall pond stability.

Post-larval shrimp (PL 9–10) sourced from the same hatchery were stocked in the late afternoon to minimize environmental stress. Prior to release, the PLs were acclimated for 1 hour to match the water temperature, pH, salinity, and dissolved oxygen of the transport medium to those of the pond water. Although both ponds were managed using uniform SOPs, natural variability in environmental conditions led to differences in phytoplankton dynamics. Based on the phytoplankton data collected throughout the culture period, pond C3 was classified as having a high Cyanophyta abundance (HC), whereas pond D2 exhibited low Cyanophyta abundance (LC). This categorization served as the basis for the comparative analysis of water quality parameters and Cyanophyta proliferation.

Feeding management in both ponds was performed manually using a combination of blind and demand-feeding strategies. The feed types were adjusted according to the shrimp growth stages, as shown in Table 2. PT Suri Tani Pemuka supplied all feeds that had protein levels ranging from 32% to 36%. During days 1–7 of culture (DOC 1–7), 3 kg of feed was provided per 100,000 shrimp. The feed amounts were gradually increased to 200 g day^{-1} per 100,000 shrimp for DOC 8–15, 400 g day^{-1} per 100,000 shrimp for DOC 16–26, and 1 kg day^{-1} per 100,000 shrimp for DOC 27–30. From DOC 31 until harvest, the feeding regime was

Table 1. Pond characteristics, shrimp source, and stocking information in intensive whiteleg shrimp cultivation with different Cyanophyta abundance at PT Pyramide Paramount Indonesia, Farm Goris, Buleleng Regency, Bali, Indonesia

Pond codes	Shrimp source	Stocking date	Pond size (m^2)	Stocking density (ind m^{-2})
C3 (HC)	PT Suri Tani Pemuka	01 August 2024	3,238	116
D2 (LC)	PT Suri Tani Pemuka	03 July 2024	3,461	196

Note: HC = High Cyanophyta abundance; LC = Low Cyanophyta abundance.

changed to a demand feeding method. During this phase, feed allocation was determined based on biomass estimations and a calculated feeding rate, which was adjusted according to shrimp weight and appetite.

Water quality management involved routine siphoning, water replacement, and probiotic application. Siphoning began on day 30 and was performed every three days to remove organic waste, uneaten feed, and sludge from the pond bottom, particularly around the central drainage area. The water lost during this process was replaced with sterilized seawater up to a water level of 5–10 cm in the pond. Regular use of probiotics helped maintain microbial balance, decompose organic matter, and support both water quality and shrimp health throughout the culture period.

Water Quality Measurement

Daily *in-situ* monitoring focused on physicochemical parameters, including DO, temperature, and salinity, which were measured using multiparameter water quality probes. The pH was measured separately using a calibrated digital pH meter. Measurements were consistently taken in the morning from representative locations in each pond to ensure reliability and to minimize variability.

Weekly *ex-situ* analyses were performed to assess the chemical and microbiological parameters. Water samples were collected and analyzed in an on site laboratory. Total organic matter (TOM) and alkalinity were measured using standard titration methods, following the procedures outlined in the APHA (2017) guidelines. The concentrations of ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and phosphate (PO_4^{3-}) were determined using commercial colorimetric test kits specifically designed for aquaculture water analysis, following the manufacturer's protocols.

The microbial assessment focused on the total count of *Vibrio* species. Water samples were serially diluted, cultured on thiosulfate citrate bile salts sucrose (TCBS) agar, and incubated at room temperature. Colony-forming units (CFU) were counted using the total plate count method to estimate the density of *Vibrio* in pond water.

Abundance and Composition of Cyanophyta Observation

The abundance and composition of Cyanophyta were monitored on a weekly basis to assess phytoplankton dynamics in relation to water quality parameters. Surface water samples were collected from each pond at a depth of approximately 30-50 cm, following the method described by Do *et al*. (2025). At four predefined equidistant locations around the perimeter of each pond, 1,000 mL of water was sampled using a 1-L sample bottle. Subsequently, a 250 mL water sample was

Table 2. Feed codes, forms, nutritional composition, and application periods in intensive whiteleg shrimp culture at PT Pyramide Paramount Indonesia, Farm Goris, Buleleng Regency, Bali, Indonesia

Brand and code	Form	Protein (%)	Feed size (mm)	DOC	Shrimp weight (g)
STP SGH C0	Powder	36		1–5	< 0.1
STP SGH C1, SGH C2	Crumble	36	0.4–0.8, 0.8–1.0	6–30	0.5–2.0
STP P1,0-SGH P1,8	Pellet	32	1.0–1.8 x 1.0–2.7	31–harvest	2.0–> 21

taken from the samples and combined into a 1-L composite sample, which will be used to ensure a representative sample of the pond. All sampling was conducted in the morning (between 07:30 and 09:00) to minimize diurnal variation.

Samples were immediately preserved with Lugol's iodine solution (1% final concentration) to maintain cellular integrity for microscopic analysis. For enumeration, a 50 mL aliquot of each preserved sample was allowed to settle for 24 hours in a graduated cylinder. The supernatant was carefully aspirated, and the concentrated sample was adjusted to a final volume of 5 mL with methanol.

Quantitative observations were conducted using a Neubauer counting chamber (depth: 0.100 mm; area: 0.0025 mm^2 per small square) under a binocular microscope at 40× magnification. Two independent chambers were filled with each concentrated sample, and the samples were counted as replicates. A minimum of 10 major squares (each containing 16 small squares) were enumerated per chamber, or counting continued until at least 100 Cyanophyta cells or colonies were counted per chamber. Filamentous Cyanophyta (e.g., *Oscillatoria*) were counted by estimating the number of cells per filament based on average filament length and cell size. Cell abundance was calculated using the standard hemocytometer formula and expressed as cells per milliliter (cells mL^{-1}).

Cyanophyta composition was identified based on morphological characteristics, such as cell shape, colony formation, and pigmentation, observed under a microscope. General taxonomic classification was conducted using standard identification keys commonly used for marine and brackish water environments. These include reference works by Newell & Newell (1963), Subrahmanyan (1958), Santhanam *et al.* (1987), and Tomas (1997), which provide comprehensive guidance for identifying phytoplankton groups in coastal and aquaculture systems.

Growth and Production Performance Analysis

Shrimp growth was monitored weekly throughout the culture period to evaluate the performance under varying environmental conditions. Growth sampling was conducted using a cast net, which enabled the random collection of representative shrimp samples from various point of pond areas. Shrimp samples were collected from three equidistant sampling points around the pond perimeter. After sampling, the shrimp were collected, and 30 individuals shrimp were weighed using a digital scale to determine their average body weight (ABW). Based on changes in ABW over time, the average daily growth (ADG) was calculated to assess the growth rate during the culture cycle.

In addition to weekly monitoring, production performance data were recorded at harvest. The parameters evaluated included final biomass (total harvest weight), final ABW, final ADG, feed conversion ratio (FCR), survival rate (SR), and pond productivity. These indicators provided an overall assessment of shrimp performance and feed efficiency under the respective environmental and management conditions of each pond.

Data Analysis

To assess the relationship between environmental factors and phytoplankton dynamics, statistical analyses were conducted on selected water quality parameters. Ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), total organic matter (TOM), dissolved oxygen (DO), and Cyanophyta abundance were initially analyzed using Pearson correlation to evaluate bivariate linear associations.

Additionally, multiple linear regression analysis was conducted to determine the combined influence of water quality parameters on Cyanophyta abundance. The initial regression model included all six water quality parameters and pond type as independent variables. However, diagnostic analysis revealed high multicollinearity between nitrate and phosphate ($r = 0.814$, VIF > 3.8), reflecting their interdependent biogeochemical cycling in aquaculture systems. Following established statistical practice for addressing multicollinearity, nitrate was excluded from the final model to improve parameter stability and model interpretability. The final regression model included six predictors: ammonium, nitrite, phosphate, TOM, DO, and pond type.

The assumptions of linearity, normality of residuals, and homoscedasticity were verified using residual and normal probability plots. Multicollinearity was assessed using variance inflation factors (VIF), with values < 5 considered acceptable. Both correlation and regression analyses were conducted using IBM SPSS Statistics (version 20).

Other water quality parameters, including temperature, salinity, pH, alkalinity, and total *Vibrio* counts, were presented using descriptive statistics, specifically as mean values and ranges observed during the culture period. Similarly, shrimp production performance metrics, such as final biomass, final ABW, final ADG, FCR, SR, and productivity, were summarized descriptively to provide a comparative overview of the ponds.

Ethical Statement

Ethical guidelines regarding animal care and handling were strictly adhered to throughout the study, ensuring that no shrimp experienced injury, stress, or inappropriate treatment. Whiteleg shrimp cultivation activities were conducted following PT Piramyde Paramount Indonesia’s institutional protocol and adhering to SNI 8228.1:2015, which strictly regulates biosecurity, feeding management, and water quality control. This study focused on regular water quality monitoring and did not involve experimental procedures using live animals. Water sampling was conducted non-invasively from the farm ponds without disrupting shrimp rearing activities. Shrimp production data used in the study were obtained entirely from harvest records provided by the farm for production performance analysis. During the study, no direct handling, special treatment, or interventions were performed on live shrimp. Therefore, this study did not require formal ethical approval as all activities fell within the scope of existing environmental monitoring and production data analysis. All research procedures were conducted in accordance with standard aquaculture monitoring practices and with official permission from the farm management.

RESULTS AND DISCUSSION

Cyanophyta Abundance and Composition

Observations showed a clear distinction in Cyanophyta dynamics between the HC (Pond C3) and LC (Pond D2) ponds (Figure 1). Cyanophyta dominance was notably higher in HC, averaging 7.09%, compared to 3.47% in LC. Similarly, the average cell abundance in the HC pond (47,400 cells mL^{-1}) was more than twice that of the LC pond (18,250 cells mL^{-1}). HC sharply spiked during week 2, exceeding 240,000 cells mL^{-1}, followed by a rapid decline and stabilization. In contrast, LC showed more consistent Cyanophyta levels, with a mild peak in week 3 and concentrations generally ranging between 10,000 and 40,000 cells mL^{-1} throughout the culture period.

The total phytoplankton abundance in both ponds is illustrated in Figure 2. The HC pond had a higher average density (668,250 cells mL^{-1}) than the LC pond (526,400 cells mL^{-1}). While both exhibited fluctuations, HC experienced earlier and multiple peaks, whereas LC showed a delayed but sharper bloom around weeks 5–6.

Figure 3 shows that *Oscillatoria* dominated the Cyanophyta composition in both ponds but at different magnitudes. In the HC pond, *Oscillatoria* reached 435,000 cells mL^{-1}, followed by *Anabaena* (21,500 cells mL^{-1}) and *Microcystis* (17,500 cells mL^{-1}). In contrast, the LC pond had lower overall densities, with *Oscillatoria* at 175,000 cells mL^{-1}, followed by *Microcystis* (5,000 cells mL^{-1}) and *Anabaena* (2,500 cells mL^{-1}).

The results clearly show that the HC pond exhibited significantly higher Cyanophyta presence, both in terms of absolute abundance and relative dominance within the phytoplankton community (Figure 1). This trend aligned with the overall phytoplankton dynamics (Figure 2) and genus composition (Figure 3), in which *Oscillatoria* dominated both ponds but reached much higher levels in the HC pond. The earlier and more frequent peaks observed in the HC also suggest that this pond was more prone to bloom events.

The dominance of bloom-forming Cyanophyta genera, such as *Oscillatoria*, *Anabaena*, and *Microcystis*, in the HC pond indicates a potential ecological imbalance in the pond. These genera are often associated with eutrophic conditions and elevated nutrient concentrations, particularly nitrogen and phosphorus, which can stimulate excessive growth (Li *et al*., 2016; Yang *et al*., 2025; Zhang *et al*., 2016). The earlier spike and greater variability in Cyanophyta abundance in HC likely reflect unstable environmental conditions, possibly driven by fluctuating nutrient inputs, low grazing pressures, or reduced phytoplankton diversity. Such instability often precedes harmful algal blooms (HABs), which cause oxygen depletion, toxin production, and increased stress on aquaculture organisms (Díaz-Tapia *et al*., 2019). Although both ponds were managed under uniform standard operating procedures, the clear disparity in Cyanophyta dynamics underscores the role of internal pond conditions. Factors

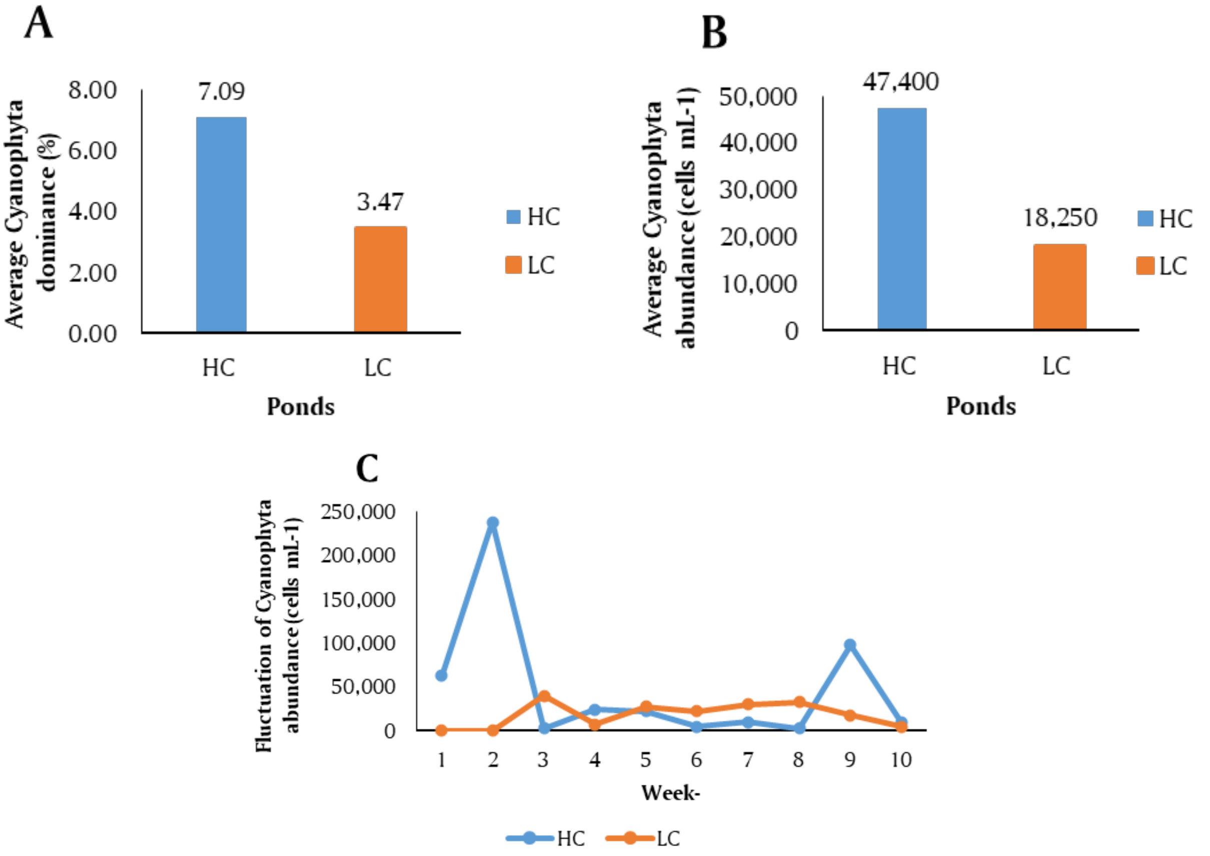

Figure 1. Cyanophyta dynamics in intensive whiteleg shrimp ponds over the 10-week culture period. (A) Average Cyanophyta dominance as a percentage of the total phytoplankton community. (B) Average Cyanophyta abundance (cells mL^{-1}). (C) Weekly fluctuation of Cyanophyta abundance. HC: high Cyanophyta abundance pond; LC: low Cyanophyta abundance pond

such as organic matter accumulation, reduced light penetration, and microbial interactions appear to significantly influence phytoplankton structure, which is consistent with previous studies on bloom susceptibility in aquatic systems (Silva *et al*., 2025). The persistent dominance of *Oscillatoria* in HC also raises concerns regarding benthic bloom formation and increased sediment oxygen demand. As filamentous *Oscillatoria* proliferates, it can trap organic matter, enhance microbial respiration, and contribute to hypoxic conditions at the pond bottom. Moreover, its abundance has been linked to elevated *Vibrio* densities, which pose a risk of disease outbreaks and reduced shrimp survival (Ariadi *et al*., 2019). Taken together, these findings suggest that Cyanophyta dynamics, particularly the proliferation of bloom-forming genera, can serve as early ecological indicators of pond instability. These patterns are directly related to the subsequent analysis of water quality

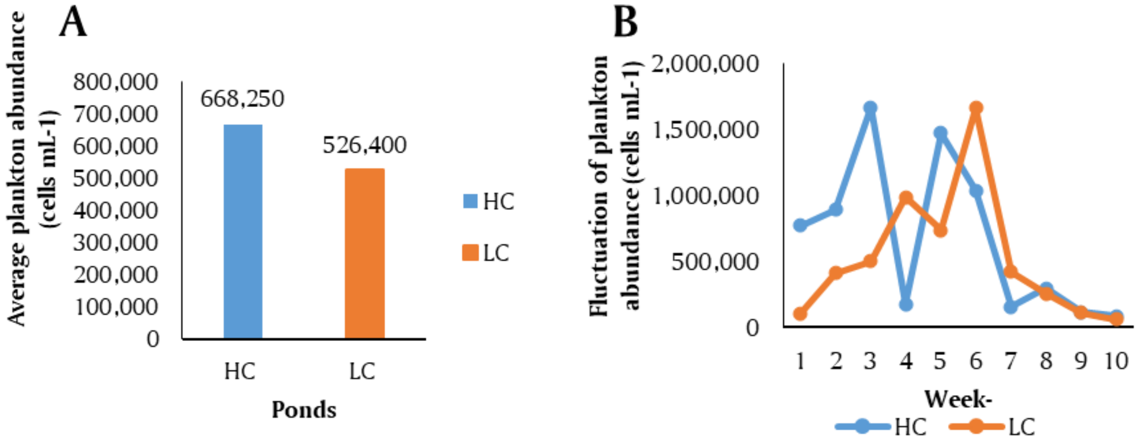

Figure 2. Total phytoplankton dynamics in intensive whiteleg shrimp ponds during a 10-week monitoring period. (A) Average total phytoplankton abundance (cells mL^{-1}). (B) Weekly fluctuation of total phytoplankton abundance (cells mL^{-1}). Data were based on weekly sampling (n = 10 data points per pond). HC: high Cyanophyta abundance pond; LC: low Cyanophyta abundance pond

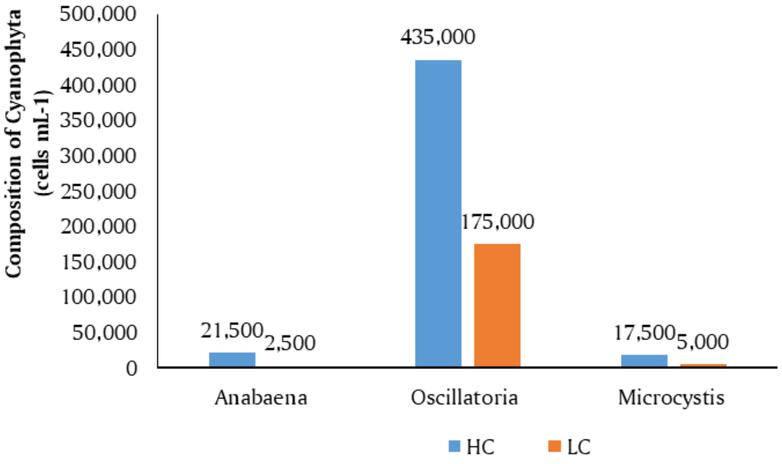

Figure 3. Genus-level composition of Cyanophyta communities in intensive whiteleg shrimp ponds throughout the culture period. Data represent the average abundance (cells mL^{-1}) of the dominant genera from weekly samples (n = 10). HC: high Cyanophyta abundance pond; LC: low Cyanophyta abundance pond

parameters, including dissolved oxygen, nutrients, and organic matter, and how they interact to influence overall pond performance.

Water Quality

Table 3 presents the ranges of key water quality parameters recorded in the HC and LC ponds during the culture period, benchmarked against the optimal standards for whiteleg shrimp farming (PERMEN KP No. 75 of 2016). Values represent the minimum-maximum ranges observed during weekly monitoring (n = 10 data points). Both ponds maintained salinity, temperature, and pH within the acceptable ranges. Salinity fluctuated between 30 and 39 ppt in the HC and 32 and 40 ppt in the LC, slightly exceeding the upper limit of the recommended range (26–32 ppt). However, whiteleg shrimp demonstrate relatively stable growth and high survival rates between 32-40 ppt, with optimal performance observed at approximately 35 ppt (Ayaz *et al*., 2015; Liu *et al*., 2024). Temperatures were suitable for shrimp growth, ranging from 27 to 32°C in HC and from 27 to 29°C in LC. The pH values were relatively stable in both ponds, with HC ranging from 7.5 to 8.6 and LC from 7.4 to 8.9, generally aligning with the optimal range of 7.5–8.5. Key differences included consistently high total organic matter (TOM) exceeding the recommended levels in both ponds and marginal DO reduction in the HC pond, potentially linked to higher biological activity.

Figure 4 illustrates the weekly fluctuations in the dissolved oxygen (levels across both ponds. DO levels in HC ranged from 4.0 to 4.9 mg L^{-1}, while LC ranged from 4.0 to 4.8 mg L^{-1}, with both ponds maintaining values at or above the minimum threshold ($\geq$ 4 mg L^{-1}) for whiteleg shrimp. However, HC consistently showed slightly lower DO levels than LC. This marginal reduction may be attributed to the higher biological oxygen demand resulting from increased Cyanophyta abundance and elevated organic matter concentrations (Huisman *et al*., 2018).

Figure 5 shows that TOM levels remained consistently high in both ponds throughout the culture period. TOM concentrations ranged from 112 to 120 mg L^{-1} in HC and from 110 to 120 mg L^{-1} in LC, exceeding the recommended

Table 3. Water quality parameter ranges in ponds with high (HC) and low (LC) Cyanophyta abundance throughout the intensive whiteleg shrimp farming cycle (August-November 2024)

Parameter	Range		Optimum (PERMEN KP No. 75/2016)
	HC	LC	
Salinity (ppt)	30−39	32−40	26−32
Temperature (°C)	27−32	27−29	>27
Dissolved oxygen (mg L^{-1})	4.0−4.9	4.0−4.8	≥4
pH	7.5−8.6	7.4−8.9	7.5−8.5
Alkalinity (mg L^{-1})	146−210	126−202	100−150
Total organic matter (mg L^{-1})	112−120	110−120	≤90
Ammonium (mg L^{-1})	0.1−1.0	0.1−2.0	−
Nitrite (mg L^{-1})	0.01−0.10	0.01−0.15	≤1
Nitrate (mg L^{-1})	26−28	26−30	−
Phosphate (mg L^{-1})	0.20−2.00	0.20−2.00	0.1−5
Total *Vibrio* count (CFU mL^{-1})	350−4,460	420−3,780	≤1 x 10^3

Note: HC = High Cyanophyta abundance; LC = Low Cyanophyta abundance threshold of ≤ 90 mg L^{-1}. These elevated levels indicate substantial organic loading, likely from residual feed, shrimp excretion, and microbial biomass. Although both ponds had similar TOM levels, Cyanophyta abundance was notably higher in HC, suggesting that additional factors, such as nutrient availability or oxygen conditions, may have contributed to phytoplankton dominance.

Figure 6 presents weekly fluctuations of key nitrogenous compounds: ammonium (A), nitrite (B), and nitrate (C). Ammonium levels varied throughout the culture period, with both ponds showing mid-cycle peaks. LC recorded higher spikes, reaching up to 2.0 mg L^{-1}, compared to 1.5 mg L^{-1} in HC, possibly due to reduced microbial assimilation or lower phytoplankton uptake. Nitrite concentrations remained within the safety threshold (≤1 mg L^{-1}) in both ponds, though LC exhibited a late increase to 0.15 mg L^{-1}, potentially indicating incomplete nitrification under microbial stress. Nitrate levels showed a steady accumulation, plateauing between weeks 6–9. HC maintained slightly more stable nitrate concentrations (26–28 mg L^{-1}) than LC (26–30 mg L^{-1}), reflecting ongoing ammonium conversion through nitrification.

Figure 7 shows that phosphate concentrations rose steadily in both

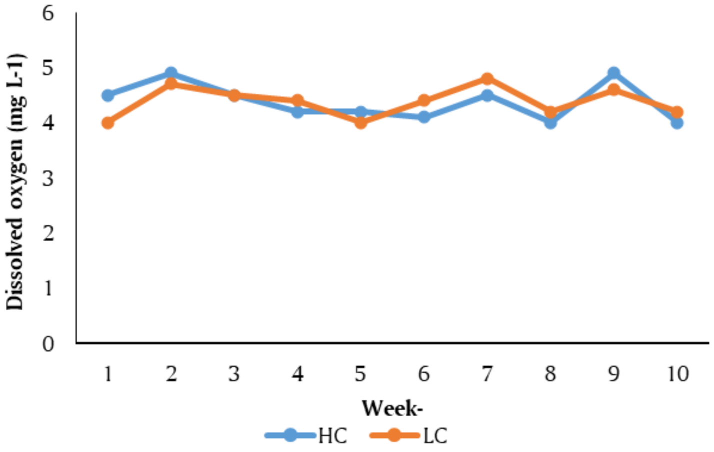

Figure 4. Weekly dissolved oxygen (DO) fluctuations in intensive whiteleg shrimp ponds during the 10-week culture period. HC: high Cyanophyta abundance pond; LC: low Cyanophyta abundance pond

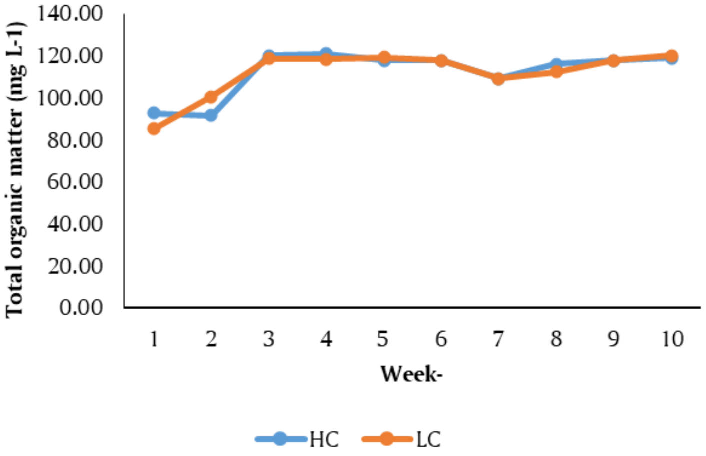

Figure 5. Weekly total organic matter (TOM) concentrations in intensive whiteleg shrimp ponds throughout the culture cycle. HC: high Cyanophyta abundance pond; LC: low Cyanophyta abundance pond

ponds, peaking between weeks 6 and 9 at approximately 2.0 mg L^{-1}. This upward trend coincided with the period of Cyanophyta proliferation in the HC pond, suggesting that elevated phosphorus levels may have supported phytoplankton growth. Although both ponds experienced similar phosphate peaks, the higher Cyanophyta abundance in HC implies that other environmental conditions may have amplified the biological response to

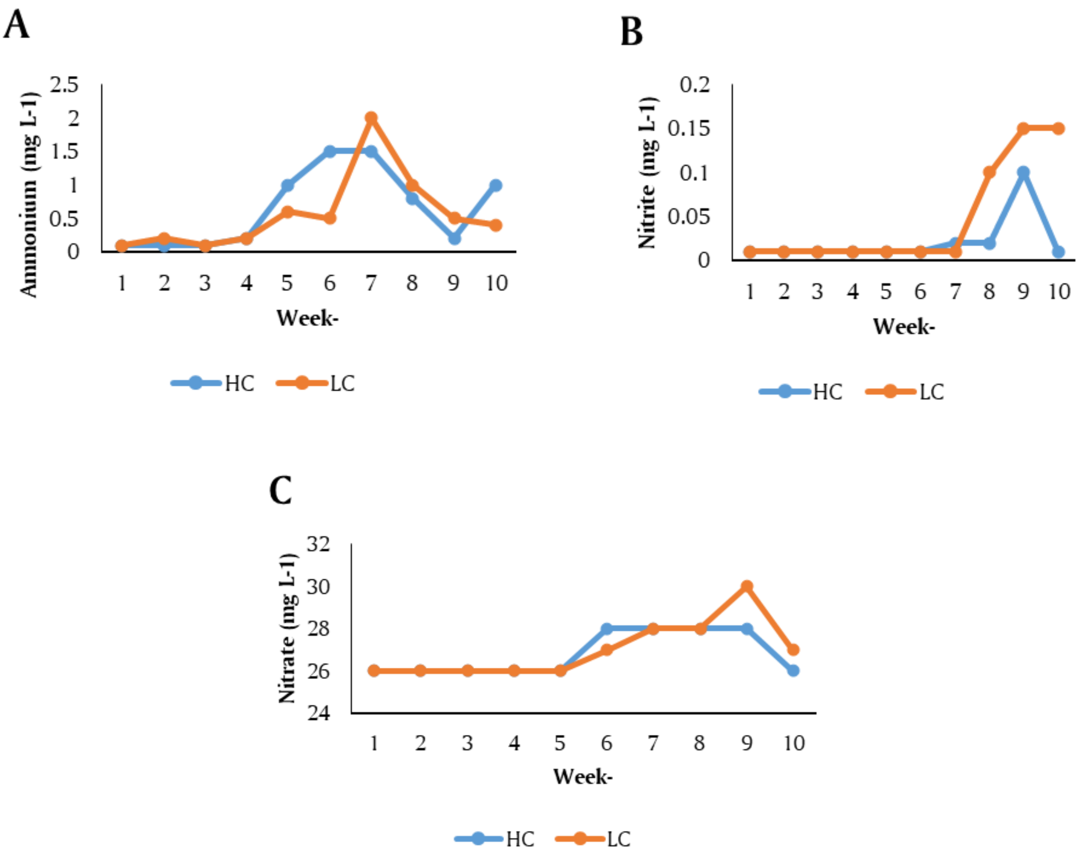

Figure 6. Weekly fluctuations of nitrogenous compounds in intensive whiteleg shrimp ponds over the 10-week monitoring period. (A) Ammonium (NH_4^+) concentrations (mg L^{-1}). (B) Nitrite (NO_2^-) concentrations (mg L^{-1}). (C) Nitrate (NO_3^-) concentrations (mg L^{-1}). HC: high Cyanophyta abundance pond; LC: low Cyanophyta abundance pond

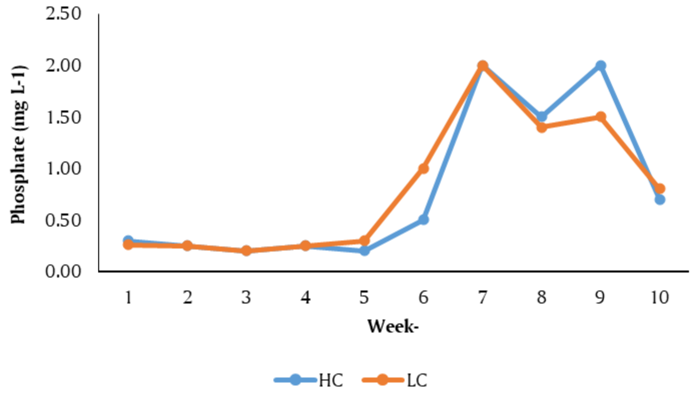

Figure 7. Weekly phosphate (PO_4^{3-}) concentration fluctuations in intensive whiteleg shrimp ponds during the culture period. HC: high Cyanophyta abundance pond; LC: low Cyanophyta abundance pond

phosphorus enrichment.

The water quality parameters measured in both ponds offer insights into the environmental drivers that may have influenced Cyanophyta dynamics, as discussed in the previous subsection. Although temperature and pH remained within optimal limits for shrimp culture in both HC and LC ponds (PERMEN KP No. 75/2016), variations in salinity and nutrient concentrations suggest differential ecological pressures that may have shaped phytoplankton behavior and bloom risk. Dissolved oxygen dynamics during the shrimp grow-out period may have influenced Cyanophyta abundance in both ponds.

The positive correlation between dissolved oxygen (DO) and Cyanophyta abundance ($r = 0.566$, $p < 0.01$, Table 4) indicates complex ecological feedback mechanisms characteristic of intensive aquaculture systems. During daylight hours, Cyanophyta actively produce oxygen through photosynthesis (Lazár *et al*., 2022), potentially creating localized supersaturation that may further favor their competitive advantage over other phytoplankton. This photosynthetic activity can establish a positive feedback loop, in which initial Cyanophyta growth enhances DO conditions, which subsequently support further proliferation. However, this relationship becomes ecologically precarious during blooms or at night, when algae consume more oxygen due to increased respiration, causing oxygen depletion (Cui *et al*., 2024), potentially leading to hypoxic conditions that stress shrimp populations (Wang *et al*., 2021). The dual role of Cyanophyta, as both oxygen producers and consumers, underscores the importance of maintaining balanced phytoplankton communities for pond stability, rather than attempting to eradicate Cyanophyta completely.

The consistently elevated TOM levels (112-120 mg L^{-1}), exceeding recommended thresholds by 25-33%, created conditions favourable for dynamic microbial-nutrient interactions in the pond. High organic matter loading stimulates heterotrophic bacterial activity (Alfiansah *et al*., 2018), which competes with phytoplankton for available nutrients and simultaneously consumes oxygen during decomposition. This microbial processing of organic matter likely influenced nutrient bioavailability through mineralization-immobilization dynamics (Torres-Beristain, 2005), where nutrients are either released for phytoplankton uptake or incorporated into microbial biomass. The similar TOM levels in both ponds, paired with markedly different responses of Cyanophyta, suggest that the state and processing of organic matter, rather than its mere presence, determined ecological outcomes. In the HC pond, conditions may have favored pathways of organic matter decomposition, enhancing nutrient recycling and bioavailability, creating a more favorable environment for Cyanophyta proliferation despite similar initial organic loads in the two ponds. These complex interactions between organic matter processing and algae proliferation align with recent findings that highlight the synergistic role of residual feed organic matter in promoting cyanobacterial blooms in aquaculture systems (Wang *et al*., 2023)

Phosphate concentrations increased concurrently in both ponds, peaking between weeks six and nine, but the biological response differed markedly. The stronger bloom response in HC suggests that this pond was more sensitive to phosphorus loading, possibly due to the pre-existing dominance of bloom-forming Cyanophyta genera. Phosphorus is widely recognized as a limiting nutrient in many aquatic systems, and its enrichment, especially under favorable light and temperature conditions, can accelerate the growth of Cyanophyta (Sadegh *et al*., 2021).

Overall, despite being managed under similar operational protocols, the combined effects of slightly lower DO, persistently high organic matter, and phosphorus enrichment appear to have created more favorable conditions for Cyanophyta proliferation in HC than in LC. These findings emphasize the role of pond-specific ecological feedback in modulating bloom risk and underscore the importance of integrated water quality monitoring to inform predictive bloom management in intensive shrimp aquaculture.

Correlation among Ammonium, Nitrite, Nitrate, Phosphate, Total Organic Matter, Dissolved Oxygen, and Cyanophyta Abundance

Pearson's correlation analysis revealed varying degrees of association between Cyanophyta abundance and selected water quality parameters (Table 4). The analysis was based on pooled weekly data from both ponds (total n = 20 observations). Among the seven parameters evaluated, only dissolved oxygen (DO) showed a statistically significant positive correlation with Cyanophyta abundance (r = 0.566, $p < 0.01$), whereas the other parameters exhibited weak or non-significant associations, suggesting complex multifactorial influences on Cyanophyta dynamics beyond simple nutrient availability. This relationship indicates that higher DO levels were associated with greater Cyanophyta proliferation across both ponds. The trend is consistent with the weekly DO patterns, in which the HC pond, despite having a slightly lower average DO than the LC pond, maintained levels sufficient to support photosynthetic phytoplankton activity.

Total organic matter (TOM) showed a moderate negative correlation with Cyanophyta abundance (r = -0.397), although this relationship was not statistically significant. This finding suggests that high organic loading may have had some inhibitory effect, possibly through reduced light penetration or increased microbial competition for nutrients. Nevertheless, Cyanophyta thrived in the HC pond despite TOM levels exceeding the recommended threshold, suggesting that other environmental factors may have offset potential suppression.

Ammonium exhibited a weak negative correlation with Cyanophyta (r = -0.259), whereas nitrite, nitrate, and phosphate showed very weak to negligible correlations (ranging from -0.016 to -0.116). These findings imply that the presence of these nutrients alone was not the primary driver of Cyanophyta fluctuations in this study. For example, although phosphate levels increased in both ponds between weeks six and nine, only the HC pond experienced substantial Cyanophyta blooms during that period. The complex interactions between the observed water quality parameters and other factors, such as light availability, phytoplankton competition, and microbial interactions, highlight the need to consider these variables when evaluating and controlling harmful algal bloom dynamics, including those involving Cyanophyta.

The correlation analysis in this study provides insights into the relative importance of different water quality parameters in shaping Cyanophyta dynamics in intensive shrimp ponds. Among all variables tested, dissolved oxygen (DO) was the only parameter

Table 4. Pearson correlation coefficients between Cyanophyta abundance and selected water quality parameters in intensive whiteleg shrimp ponds

Parameter	Pearson's correlation coefficient
Dissolved oxygen	0.566**
Total organic matter	-0.397
Ammonium	-0.259
Nitrite	-0.016
Nitrate	-0.116
Phosphate	-0.038

** Correlation is significant at the 0.01 level (2-tailed) that showed a statistically significant positive correlation with Cyanophyta abundance ($r = 0.566, p < 0.01$). This finding suggests that DO availability is a limiting factor for Cyanophyta growth under intensive aquaculture conditions, likely reflecting a close relationship between DO levels, phytoplankton photosynthesis, and bloom persistence in aquaculture and eutrophic systems (Wang & Zhang, 2020).

The moderate but nonsignificant negative correlation between total organic matter (TOM) and Cyanophyta abundance ($r = -0.397$) suggests that high concentrations of lightabsorbing dissolved organic carbon (DOC) may reduce light availability for phytoplankton, potentially affecting their growth and resilience. However, nutrient enrichment can shift bloom thresholds, allowing phytoplankton to thrive despite high DOC levels (Carpenter *et al*., 2022). While high organic matter can negatively impact light availability and microbial competition, nutrient enrichment and the presence of resilient species can mitigate these effects (Ratnarajah *et al*., 2021).

The weak to non-significant relationships between individual nutrients and Cyanophyta abundance in the correlation analysis suggest that, under nutrient-saturated conditions typical of intensive aquaculture systems, phytoplankton growth is constrained by factors other than nutrient concentrations alone (Table 4). In such environments, Cyanophyta growth becomes limited by other factors, such as light availability, water residence time, temperature, and vertical mixing (Chorus *et al*., 2021; Liu *et al*., 2021). This pattern supports previous findings that nitrogen concentration alone is a poor predictor of Cyanophyta proliferation when other factors that can limit or promote growth are not considered (Burford *et al*., 2023). The similar phosphate trends observed in both ponds, coupled with markedly different Cyanophyta responses, further demonstrate that bloom formation depends on the complex interplay of multiple environmental conditions and ecological interactions, rather than simple linear nutrientconcentration relationships.

From a management perspective, these findings suggest that DO dynamics may be a more reliable early indicator of the risk of Cyanophyta blooms in intensive shrimp ponds than individual nutrient measurements. The lack of strong correlations with nitrogen and phosphorus compounds suggests that standard nutrient monitoring, while essential, should be complemented by parameters that reflect biological and ecological processes. Integrating DO trends with phytoplankton composition monitoring could enhance predictive capacity for bloom events and inform proactive management strategies (Qiao *et al*., 2020)

Multiple Regression Analysis

To complement the bivariate correlations and assess the combined predictive power of water quality parameters, multiple linear regression analysis was performed. The final model only included ammonium, nitrite, phosphate, total organic matter, dissolved oxygen, and pond type (HC=1, LC=0) as predictors ($n = 20$), which excluded nitrate due to multicollinearity concerns, and explained 51.9% of the variance in Cyanophyta abundance ($R^2 = 0.519$, Adjusted $R^2 = 0.296$, $F(6,13) = 2.333$, $p = 0.094$). Although the overall model approached, but did not reach conventional statistical significance ($p = 0.094$), it explained a substantial portion of the variance in Cyanophyta dynamics.

As shown in Table 5, dissolved oxygen emerged as the only statistically significant ($p < 0.05$) predictor in the multivariate model ($\beta = 0.530$, $p = 0.035$), consistent with the Pearson correlation results. The regression coefficient (B) indicates that for each 1 mg L^{-1} increase in dissolved oxygen, Cyanophyta abundance increased by approximately 94,894 cells mL^{-1}, holding other factors constant. None of the other predictors (ammonium, nitrite, phosphate, TOM, or pond type) showed statistically significant effects when considered simultaneously with the other variables. Multicollinearity diagnostics confirmed acceptable levels for all remaining predictors, with variance inflation factors (VIF) ranging from 1.117 to 2.840, which is also below the conservative threshold of 5. Residual analysis indicated reasonable conformity with regression assumptions, supporting the validity of the model estimates.

The multiple regression analysis provides an important multivariate context for interpreting the bivariate correlation results. While the Pearson correlations identified individual relationships, the regression model demonstrates that dissolved oxygen remains the dominant predictor, even when controlling for other water quality parameters and pond differences. The significant positive relationship between DO and Cyanophyta abundance in the multivariate model reinforces the robustness of this finding. The non-significant nutrient coefficients suggest their effects may be indirect or mediated by oxygen-related processes. This pattern aligns with the concept of nutrient balance (ecological stoichiometry) in aquaculture systems, where nutrient ratios are not the only influential factors; other environmental factors, such as oxygen availability, also significantly affect algal dynamics (Akter *et al*., 2022).

Growth and Production Performance

Figure 8 illustrates weekly growth performance in the HC and LC ponds, represented by average body weight (ABW) and average daily growth (ADG). Both ponds showed steady weight gain over the 8-week period, with ABW in LC starting slightly higher and maintaining a small advantage until harvest, reaching 12.20 g ind^{-1} compared to 11.49 g ind^{-1} in HC. ADG trends varied between ponds: HC showed greater fluctuations, peaking at 0.50 g day^{-1} in week 4, whereas LC maintained a more stable growth pattern, peaking at 0.37 g day^{-1} in week 6. These trends suggest that shrimp in LC experienced more stable growth conditions, potentially linked to lower Cyanophyta abundance and more consistent water quality.

Despite the lower stocking density, HC yielded a final biomass of 3,342.931 kg with a survival rate of 77.43%. LC, with a higher stocking density, achieved a much greater biomass of 6,110.329 kg, though with a slightly lower survival rate of 73.86%. Productivity in LC reached 17.65 ton ha^{-1} compared to 10.32 ton ha^{-1} in HC. Feed intake was marginally higher in LC (7,682 kg) than in HC (7,196 kg), but feed conversion ratio (FCR) was markedly better in LC at 1.26 versus 2.15 in HC, indicating more efficient feed utilization under lower Cyanophyta conditions. These results suggest that lower Cyanophyta abundance in LC coincided with improved feed efficiency, higher biomass yield, and greater overall productivity.

The growth and production results in this study demonstrate how variations in pond

Table 5. Multiple regression analysis of water quality parameters predicting Cyanophyta abundance in intensive whiteleg shrimp ponds

Predictor	Coefficient (B)	Standard Error	p-value
Constant	-167364.792	233502.303	0.486
Ammonium	-3460.965	27030.195	0.900
Nitrite	186994.250	293851.238	0.536
Phosphate	-15365.486	25475.649	0.557
Total organic matter	-1388.246	1046.947	0.208
Dissolved oxygen*	94894.480	40372.650	0.035
Pond type	-34717.030	21289.429	0.127

** $R^2 = 0.519$, Adjusted $R^2 = 0.296$, $F(6,13) = 2.333$, $p = 0.094$
*Statistical significance at $p < 0.05$

ecology, particularly Cyanophyta abundance and associated water quality, translate into measurable differences in shrimp performance. Over the culture cycle, shrimp in the LC pond achieved slightly higher final average body weight (ABW) and more stable average daily growth (ADG) compared to the HC pond. This steady growth in LC is consistent with its lower Cyanophyta abundance, reduced bloom variability, and more stable environmental conditions reported in earlier studies.

The greater variability in ADG observed in HC, including a spike in week 4, may have been influenced by fluctuations in environmental quality associated with Cyanophyta blooms and changes in dissolved oxygen dynamics. Previous studies have shown that algal blooms can temporarily enhance food availability by increasing natural productivity (Jin *et al*., 2023), but their collapses can also cause oxygen depletion and toxin release, leading to physiological stress and slower growth rates (Am *et al*., 2016). This dual effect could explain the short-term growth peaks, followed by periods of reduced growth in HC. The final production metrics reinforced these

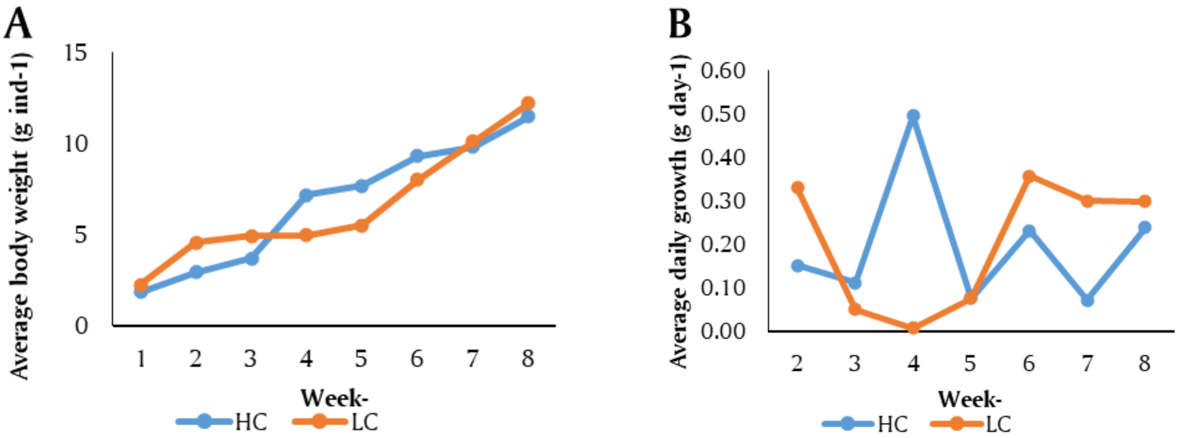

Figure 8. Weekly growth performance of whiteleg shrimp in intensive ponds with high (HC) and low (LC) Cyanophyta abundance over the 8-week sampling period. (A) Average body weight (ABW); (B) Average daily growth (ADG)

Table 6. Final production performance metrics of whiteleg shrimp cultured in intensive ponds with high (HC) and low (LC) Cyanophyta abundance

Parameter	HC	LC
Pond size (m^2)	3,238	3,461
Stocking density (ind m^{-2})	116	196
Day of culture (days)	83	81
Survival rate (%)	77.43	73.86
Final biomass (kg)	3,342.931	6,110.329
Final average body weight (g ind^{-1})	11.49	12.20
Final average daily growth (g day^{-1})	0.14	0.15
Feed intake (kg)	7,196	7,682
Feed conversion ratio	2.15	1.26
Productivity (ton ha^{-1})	10.32	17.65

patterns. The higher stocking density in the LC pond resulted in a substantially greater biomass yield (6,110.329 kg) and productivity (17.65 ton ha^{-1}) compared to HC (3,342.931 kg; 10.32 ton ha^{-1}). Notably, LC also achieved a much lower feed conversion ratio (FCR) of 1.26 compared to 2.15 in HC, indicating more efficient feed utilization under conditions of lower Cyanophyta dominance. Stable phytoplankton levels are known to promote better nutrient assimilation and growth performance in shrimp culture, supporting the view that maintaining phytoplankton within balanced limits can optimize feed efficiency and reduce waste, ultimately improving economic returns (Marinho *et al*., 2017). The slightly lower survival rate in LC (73.86%) than in HC (77.43%) is noteworthy, although the difference is modest. This finding may reflect density-related effects, in which higher stocking densities can increase competition and stress, even under favorable water-quality conditions. However, the higher biomass and productivity achieved in LC indicate that any reduction in survival was outweighed by the benefits of stable environmental conditions and effective feed use (Xu *et al*., 2025).

From an aquaculture operations perspective, these results support the view that controlling Cyanophyta abundance and preventing extreme bloom fluctuations can improve culture stability, promote consistent shrimp growth and enhance feed efficiency (Gatune *et al*., 2017). When combined with proactive water quality management, particularly maintaining adequate DO levels and controlling organic matter loads, these strategies can improve pond productivity without compromising shrimp health. This condition aligns with an earlier correlation analysis that found DO to be a more reliable indicator of bloom risk than individual nutrient measurements. Integrating biological monitoring (Cyanophyta abundance and composition) with physicochemical measurements offers a practical framework for optimizing production performance in intensive shrimp systems (Mahmudi *et al*., 2021). By prioritizing ecological stability over solely focusing on nutrient reduction alone, shrimp farmers can create conditions that sustain both environmental quality and economic benefits.

From an ecological perspective, the contrasting dynamics of Cyanophyta in the HC and LC ponds reflect the principles of disturbance ecology and competitive exclusion. The higher Cyanophyta variability and bloom-prone characteristics of the HC pond suggest a less stable ecological state, where fluctuating conditions favor opportunistic genera such as *Oscillatoria*, *Anabaena*, and *Microcystis* (Pastich *et al*., 2016; Sultana *et al*., 2024). These genera possess adaptive traits, including nitrogen fixation, buoyancy regulation, and toxin production, that confer competitive advantages under fluctuating environmental conditions (Ibelings *et al*., 2021; Pastich *et al*., 2016). In contrast, the more stable Cyanophyta levels in the LC pond may indicate a more resilient ecological state, characterized by a better-balanced phytoplankton community structure and potentially stronger top-down control through grazing pressure. This aligns with the concept of alternative stable states in aquatic ecosystems, in which similar environmental conditions can maintain different ecological communities based on historical contingencies and feedback mechanisms (Fukami, 2015; Mushet *et al*., 2020).

CONCLUSIONS

Results showed that the HC pond, with higher Cyanophyta abundance (dominated by *Oscillatoria*, *Anabaena*, and *Microcystis*), experienced greater bloom variability, slightly lower DO, and less stable growth conditions. In contrast, the LC pond maintained lower Cyanophyta levels, more stable water quality, and better production performance than the HC pond. Correlation and multiple regression analyses identified dissolved oxygen as the only parameter significantly associated with Cyanophyta abundance, underscoring its importance as a key indicator and potential driver in these systems. Nutrient concentrations alone were poor predictors of Cyanophyta dynamics, suggesting that bloom development is driven by multiple interacting factors beyond simple nutrient loading.

These findings offer several practical insights for shrimp farmers. First, monitoring of DO should be prioritized not only for direct shrimp health but also as a leading indicator of the risk of a Cyanophyta bloom. Second, management strategies should focus on maintaining a holistic balance in the ecosystem rather than targeting individual nutrients. This includes optimizing aeration to maintain DO stability, controlling organic loading through efficient feeding and sludge removal, and, if appropriate, using probiotics to enhance microbial competition against bloom-forming Cyanophyta. The superior production performance in the LC pond demonstrates that maintaining lower, stable Cyanophyta levels can directly translate into improved feed efficiency, higher biomass yield, and greater overall productivity.

Future studies should build on these findings by investigating the causal mechanisms underlying the observed DO-Cyanophyta relationship over longer time scales and across more ponds to enhance statistical power and generalizability. It would be particularly valuable to examine these dynamics in different culture systems, such as biofloc technology (BFT) or super-intensive systems with higher stocking densities, where nutrient cycling, microbial communities, and oxygen demands differ fundamentally from those in traditional intensive ponds. Research into specific management interventions, such as optimized aeration regimes, organic matter reduction techniques, and the application of targeted probiotics or algal grazers, would provide valuable data to develop standardized protocols to suppress Cyanophyta blooms. Furthermore, exploring the molecular interactions among Cyanophyta, the pond microbiome, and shrimp health could provide deeper insights into the ecological pathways that influence production outcomes.

In summary, proactively managing pond ecology to control Cyanophyta abundance and maintain dissolved oxygen stability is critical for optimizing shrimp growth, feed efficiency, and sustainable shrimp yield. Integrating routine phytoplankton monitoring with water quality analysis provides a framework for achieving profitable shrimp farming.

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AUTHOR CONTRIBUTION

AK: data curation, formal analysis, validation, visualization, writing – original draft; DASU: conceptualization, methodology, formal analysis, supervision, validation, visualization, and writing – original draft; INS: conceptualization, data curation, formal analysis, methodology, and supervision; I: formal analysis and validation; AK: project administration, visualization, and writing – original draft; SRMR: investigation, project administration, and resources; SAL: investigation, project administration, resources; MJG: investigation, project administration, and resources; IMAN: project administration, resources, and software; W: conceptualization, data curation, formal analysis, validation, visualization, and writing – original draft.

DECLARATION OF COMPETING INTEREST

The authors declare that there are no conflicts of interest related to this research or the writing of this article. All authors have read and approved the final version for publication.

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