Imbalance of Carbon–Nitrogen–Phosphorus Ratios in Coastal Waters as a Constraint for Aquaculture Development in Karawang, Indonesia

Anggoro Prihutomo[1*], *Bambang* Widigdo[2], *Sigid* Hariyadi[2], *and Syaiful* Anwar[3]

[1] Student of Natural Resources and Environmental Management, IPB University, Indonesia
[2] Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Indonesia
[3] Department of Soil Science, Faculty of Agriculture, IPB University, Indonesia

Abstract. Coastal waters are the main water source for traditional aquaculture in many regions of Indonesia, including Karawang, but their suitability is increasingly affected by nutrient enrichment and biogeochemical imbalance. This study evaluated carbon–nitrogen–phosphorus (C–N–P) ratios in Karawang coastal waters and their implications for traditional aquaculture. Water quality parameters measured included chemical oxygen demand (COD), total nitrogen (TN), ammonia (TAN), nitrite, nitrate, and phosphate. A Traffic Light Approach (TLA) was applied using criteria based on national water quality standards and relevant literature. Organic carbon was estimated from COD to determine the C/N ratio, while the N/P ratio was calculated from TN and phosphate concentrations. Results showed that ammonia (0.21–1.36 mg/L), nitrite (0.01–0.42 mg/L), and phosphate (0.018–0.898 mg/L) frequently exceeded recommended limits. Total nitrogen concentrations (4.85–9.32 mg/L) indicated eutrophic conditions. The consistently low C/N ratio (0.10–2.30) suggested carbon limitation relative to nitrogen, whereas the N/P ratio (16–953) reflected substantial nutrient imbalance. These findings indicate that Karawang coastal waters are under ecological pressure and may be less suitable as direct water sources for traditional ponds. Evaluating nutrient ratios provides a more comprehensive assessment of ecosystem condition and may support more sustainable aquaculture management.

1. Introduction

Coastal areas play a strategic role in supporting the traditional aquaculture sector in Indonesia, particularly as the primary water source for pond systems. Traditional aquaculture ponds, which are widely developed across coastal regions, including the northern coast of Java, are highly dependent on coastal water dynamics that provide water supply, natural nutrients, and environmental conditions conducive to the productivity of cultured organisms. This practice has been sustained for centuries and constitutes an integral part of coastal food production systems and local livelihoods..

However, the sustainability of coastal waters as a reliable source for aquaculture is increasingly challenged by environmental pressures, particularly declining water quality. One of the major issues is eutrophication, defined as the enrichment of water bodies due to excessive nutrient inputs, primarily nitrogen and phosphorus. Eutrophication is commonly driven by anthropogenic activities such as domestic wastewater discharge, agricultural runoff, and aquaculture operations themselves, all of which contribute substantial nutrient loads to coastal waters. This condition can trigger algal blooms, reduce dissolved oxygen levels, and disrupt the ecological balance of aquatic systems [1].

In addition to eutrophication, nutrient pollution represents another critical issue in coastal environments. Nutrients originating from terrestrial runoff, industrial effluents, as well as uneaten feed and metabolic waste from aquaculture activities, can accumulate in coastal waters and gradually degrade water quality[2]. In open aquaculture systems, this condition may accelerate the dispersion of nutrients into surrounding waters, thereby increasing the risk of large-scale eutrophication. The long-term impacts include reduced aquaculture productivity, increased disease outbreaks, and degradation of coastal ecosystems [3].

Recent reviews highlighted that nutrient pollution has become an increasingly serious environmental issue in Indonesian coastal waters, particularly in densely populated coastal regions such as the northern coast of Java (Pantura). Their review reported that approximately 82% of nutrient-related studies in Indonesian coastal waters exceeded environmental quality standards, indicating widespread nutrient enrichment and deteriorating coastal water quality. The study further emphasized that anthropogenic activities,

*Corresponding author: anggoro.prihutomo@apps.ipb.ac.id

https://doi.org/10.1051/bioconf/202624501004

including domestic wastewater discharge, agricultural runoff, industrial development, and aquaculture expansion, are major contributors to nutrient loading in Indonesian coastal ecosystems[4].These conditions are also evident in the coastal waters of Karawang, West Java, one of Indonesia's major traditional aquaculture centres. Previous studies have shown that water quality in the Karawang coastal area exhibits seasonal fluctuations with a tendency toward eutrophic conditions, largely due to the accumulation of organic waste from agricultural and aquaculture activities [5]. Furthermore, this region is subjected to significant anthropogenic pressures, including domestic and industrial waste inputs, tidal flooding associated with sea level rise, and land-use changes such as the conversion of mangroves into aquaculture ponds or industrial areas.

These pressures have the potential to further degrade coastal water quality and threaten the sustainability of traditional aquaculture systems. Therefore, a more comprehensive understanding of coastal water quality dynamics, particularly in relation to eutrophication and nutrient pollution is essential as a basis for sustainable coastal resource management in Karawang and other coastal regions in Indonesia.

Studies on coastal and aquaculture water quality in Indonesia and globally have generally focused on the analysis of single parameters, such as Chemical Oxygen Demand (COD), nitrogen (N), and phosphorus (P), as primary indicators of pollution and trophic status. While this approach provides important information on water quality conditions, it often fails to capture the complex interactions among nutrients in a comprehensive manner.

The use of single-parameter indicators tends to overlook the complexity of biogeochemical processes that involve interlinked nutrient dynamics. A key limitation of this approach is the lack of consideration of nutrient ratios, particularly carbon, nitrogen, and phosphorus (C/N/P), which are essential indicators for understanding ecosystem balance. Previous studies have demonstrated that imbalances in nutrient ratios can act as major drivers of eutrophication, in some cases exerting a stronger influence than the absolute concentrations of individual nutrients. Changes in nutrient ratios, such as altered N/P or imbalanced C/N/P, can shift phytoplankton community structure, increase the risk of harmful algal blooms, and influence biogeochemical cycling in aquatic ecosystems [6].

A stoichiometric approach based on nutrient ratios (C/N/P) has gained increasing attention due to its ability to represent ecological balance in a more holistic manner. These ratios reflect the relationship between nutrient availability and the biological requirements of aquatic organisms, and play a critical role in regulating primary productivity and ecosystem stability. In coastal aquaculture systems, nutrient imbalances often arise from disproportionate anthropogenic inputs, highlighting the importance of ratio-based approaches in evaluating environmental sustainability [6].

Despite this, studies integrating C/N/P stoichiometric analysis in the evaluation of coastal water quality—particularly in traditional aquaculture systems in Indonesia—remain limited. Therefore, there is a need for research adopting a nutrient stoichiometry approach to address this knowledge gap and to provide a more comprehensive understanding of ecosystem balance and eutrophication potential in coastal areas such as Karawang. Based on this background, this study aims to analyse water quality conditions in the coastal waters of Karawang Regency and to evaluate nutrient ratios, particularly C/N and N/P, as indicators of aquatic ecosystem balance.

2. Materials and Methods

2.1 Study Area

This study was conducted in seven coastal sub-districts in Karawang Regency, namely Cilamaya Wetan, Tempuran, Cilebar, Cibuaya, Tirtajaya, Batujaya, and Pakisjaya (Figure 1), which are part of the northern coast of Java (Pantura) and are characterized by intensive traditional aquaculture activities. The characteristics of the study area were defined based on the types of water sources used in aquaculture practices, including seawater as the primary source influenced by tidal dynamics, brackish water resulting from the mixing of seawater and freshwater in coastal and estuarine areas, and freshwater originating from rivers or terrestrial runoff.

The aquaculture systems applied in the study area are predominantly polyculture systems, with main commodities including shrimp, tilapia, and milkfish, which utilize variations in salinity and water quality conditions. These variations in water sources and environmental characteristics provide the basis for analyzing water quality dynamics, particularly in relation to C/N and N/P ratios.

2.2 Water Sampling

Water sampling was conducted at nine sampling points (T1–T9), where one sampling point represented each location. Samples were collected during the morning to midday period in October 2025, corresponding to the rainy season. Water samples were obtained using a grab sampling method, in which water was collected using a bucket and then transferred into 250 mL sample bottles. The samples were not chemically preserved; instead, they were stored in a cool box with ice to maintain low temperature and minimize changes in water quality prior to laboratory analysis

2.3 Water Quality Analysis

Water quality analysis was conducted to determine key parameters related to organic matter and nutrient dynamics. Chemical Oxygen Demand (COD) was measured using a spectrophotometric method following APHA 23rd edition (2023)[7]. Total Ammonia Nitrogen

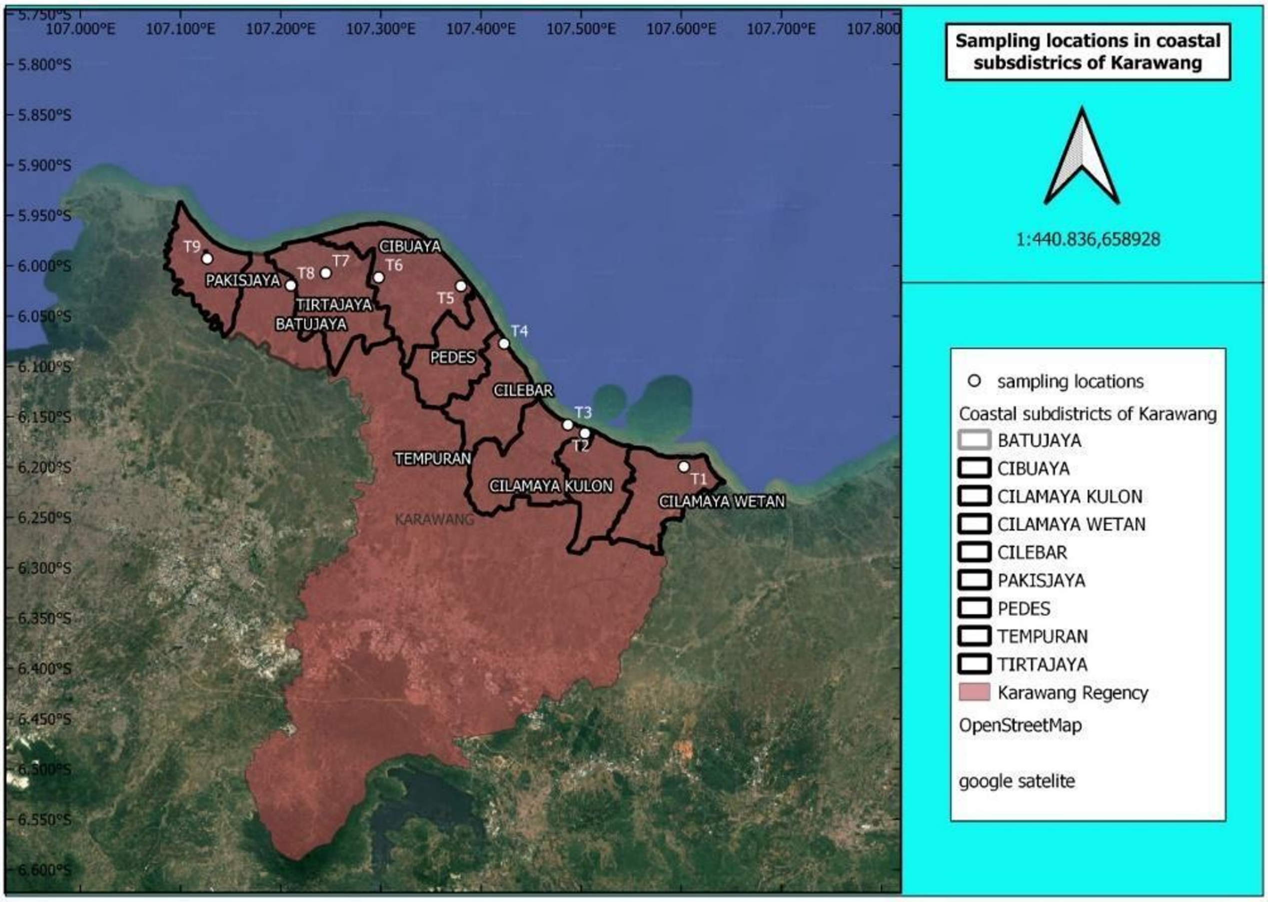

Fig. 1. Sampling locations (T1-T9) of water sources used for traditional aquaculture in the coastal area of Karawang Regency, Indonesia.

(TAN) was analyzed using the phenate method. Nitrite (NO_2^-) was determined using the sulfanilamide (diazotization) method. Nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations were measured using Hach reagent-based colorimetric methods. Total Kjeldahl Nitrogen (TKN) was analyzed following USEPA Method 351.1. Total Nitrogen (TN) was calculated as the sum of TKN, nitrite, and nitrate concentrations ($TN = TKN + NO_2^- + NO_3^-$).

2.4 Estimation of Organic Carbon and Nutrient Ratios

Organic carbon (C-organic) was estimated from COD using a conversion factor (TOC/COD ≈ 0.37), equivalent to C-organic = COD/2.67, as suggested by Wastewater Engineering: Treatment and Resource Recovery. This conversion is based on the theoretical relationship between oxygen demand and carbon oxidation, assuming that 1 mg of carbon requires approximately 2.67 mg of oxygen for complete oxidation [8]. However, this empirical relationship may vary depending on the composition and biodegradability of organic matter present in the water samples.

Organic carbon and nutrient ratios were calculated to evaluate nutrient balance in the water sources. The C/N ratio was determined as the ratio between estimated C-organic (derived from COD) and Total Nitrogen (TN), while the N/P ratio was calculated as the ratio between TN and phosphate (PO_4^{3-}). All ratios were expressed on a mass basis (mg/L) to maintain consistency with measured parameters. These ratios were used to assess nutrient dynamics and identify potential nutrient limitations in the studied water sources.

2.5 Traffic Light Approach (TLA)

The Traffic Light Approach (TLA) was applied using a fuzzy-based scoring system to evaluate water quality status. This approach classifies conditions into three categories: green (good), yellow (moderate/caution), and red (poor), while allowing smooth transitions between categories. Threshold values for each parameter were derived from national water quality standards (PP 22/2021) and relevant scientific literature.

Each water quality parameter was first normalized into a continuous score ranging from 0 to 10. Fuzzy classification was then performed using overlapping membership functions to assign each score a degree of membership to the three categories. The membership functions were defined using triangular shapes; for example, the moderate (yellow) category was represented by a triangular function with a lower bound of 2.5, a peak at 5, and an upper bound of 7.5. This configuration allows intermediate values to partially belong to adjacent categories, thereby avoiding rigid classification boundaries. The final category for each parameter was determined using the maximum membership principle, whereby the category with the highest membership value was assigned.

2.6 Data Analysis

Data were analyzed using descriptive statistics to summarize the distribution of water quality parameters across sampling locations. The measured values were then compared with applicable standards, particularly Government Regulation in PP 22/2021 and relevant scientific references, to evaluate overall environmental quality and ecological condition. Furthermore, nutrient ratios (C/N and N/P) were interpreted to identify potential imbalances and limiting nutrients within the aquatic system, providing insights into ecosystem functioning and nutrient dynamics.

3. Results and Discussion

3.1 Water Quality Characteristics

The measured water quality parameters across the sampling locations in Karawang Regency exhibited considerable variation, reflecting heterogeneous environmental conditions of the water sources. As seen in Table 1, Salinity varied widely from 0 to 30 ppt, representing a clear gradient from freshwater to marine-dominated sources.

Total Ammonia Nitrogen (TAN) concentrations ranged from 0.211 to 1.361 mg/L and showed a clear decreasing trend with increasing salinity. In estuarine and aquaculture systems, TAN concentrations below 0.5 mg/L are generally considered suitable for aquatic organisms, whereas concentrations exceeding 1 mg/L may induce physiological stress, particularly under elevated pH and temperature conditions due to the increased proportion of toxic unionized ammonia (NH_3)[9].

The highest values were observed in low-salinity conditions, particularly at Cibuaya 2 (0 ppt), indicating strong terrestrial inputs such as runoff and aquaculture discharge. Conversely, lower TAN concentrations in high-salinity areas (e.g., T2; 30 ppt) suggest dilution effects and possible transformation into oxidized nitrogen forms. This pattern confirms that salinity plays a key role in regulating ammonia distribution.

Nitrite (NO_2^-) concentrations varied between 0.010 and 0.419 mg/L, with no consistent trend along the salinity gradient. The highest value was observed at 0 ppt, while very low concentrations (<0.05 mg/L) occurred across several locations. This scattered distribution reflects the unstable nature of nitrite as an intermediate compound in nitrification and denitrification processes, making it highly sensitive to localized environmental conditions rather than salinity alone. Recommended nitrite concentrations for aquaculture waters are generally below 0.06 mg/L because elevated levels may be toxic to fish and shrimp by interfering with oxygen transport mechanisms [9]. The occurrence of concentrations above this threshold at several sites suggests incomplete nitrification and localized organic pollution.

Total Kjeldahl Nitrogen (TKN) values ranged from 2.67 to 5.25 mg/L and did not show a strong relationship with salinity (Fig.2). Natural estuarine waters commonly exhibit TKN concentrations below 2 mg/L[9]. Elevated concentrations were observed in both brackish (T5; 16 ppt) and moderate salinity areas, suggesting that organic nitrogen inputs are relatively distributed across locations. This indicates that TKN is more influenced by local sources such as feed residues, organic matter accumulation, and aquaculture activities than by salinity-driven dilution.

Table 1. Water quality characteristics of source waters used for traditional aquaculture in Karawang Regency.

Location	Salinity (ppt)	TAN (mgL^{-1})	NO_2^- (mgL^{-1})	NO_3^- (mgL^{-1})	PO_4^{3-} (mgL^{-1})	COD (mgL^{-1})	TKN (mgL^{-1})
T1	23	0.994	0.360	12.307	0.018	35.210	2.83
T2	30	0.211	0.039	13.317	0.156	35.210	3.42
T3	5	0.301	0.105	11.846	0.546	19.560	2.67
T4	15	0.642	0.102	10.193	0.132	27.340	3.00
T5	16	1.124	0.087	17.933	0.739	16.800	5.25
T6	0	1.361	0.419	9.826	0.668	1.680	3.08
T7	14	0.413	0.010	9.369	0.273	10.800	4.00
T8	5	0.819	0.036	5.188	0.408	4.200	3.67
T9	20	0.899	0.010	9.002	0.898	33.600	2.83

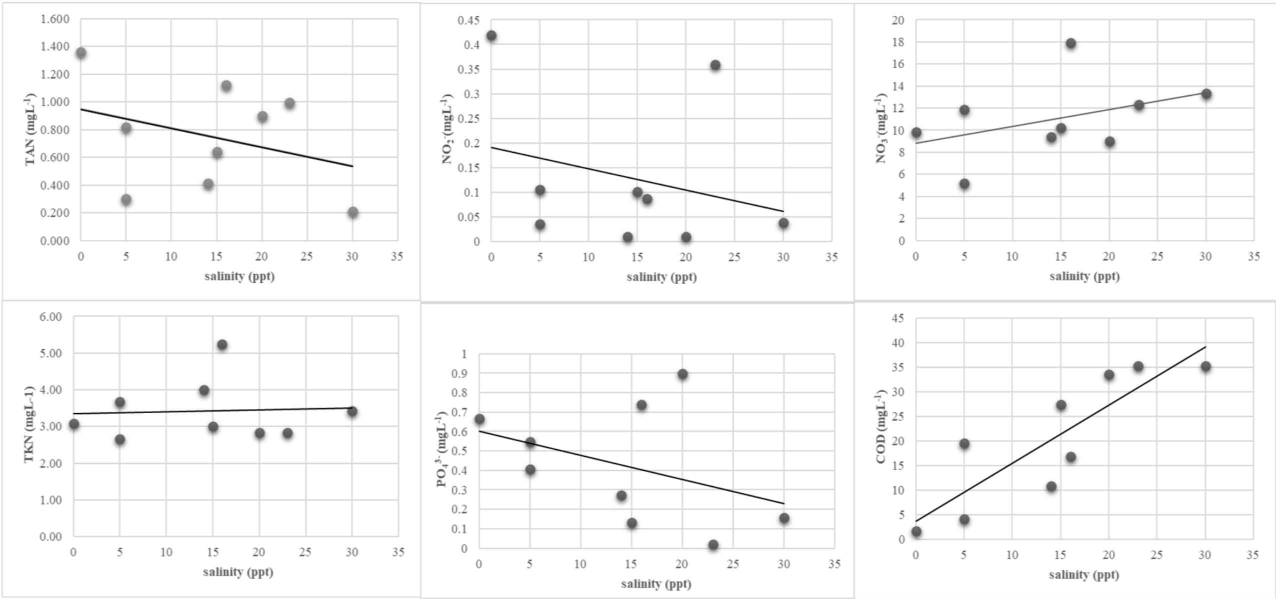

Fig. 2. Relationship between salinity and selected water quality parameters (TAN, NO_2^-, NO_3^-, PO_4^{3-}, COD, and TKN) in Karawang Regency.

Nitrate (NO_3^-) concentrations ranged from 5.19 to 17.93 mg/L and generally increased toward brackish to moderately saline conditions. The highest concentration was observed at T5 (16 ppt), suggesting active nitrification processes in mixing zones. Lower values in freshwater and some marine locations indicate that nitrate formation is likely enhanced under intermediate salinity conditions where oxygen availability and microbial activity are favorable. Concentrations below 10 mg/L are commonly regarded as acceptable for maintaining balanced aquatic productivity and minimizing eutrophication risks in aquaculture systems [9].

Phosphate (PO_4^{3-}) concentrations showed a wide range (0.018–0.898 mg/L) with no clear linear relationship with salinity. The highest values were observed in both brackish and marine-influenced sites (e.g., T5 and T9), while the lowest occurred in high-salinity conditions (e.g., T1). This variability indicates that phosphate dynamics are controlled by multiple factors, including sediment interactions, biological uptake, and localized inputs, rather than salinity alone. In coastal and estuarine ecosystems, phosphate concentrations below 0.1 mg/L are generally associated with oligotrophic to mesotrophic conditions, while higher concentrations may indicate eutrophication [2]

Chemical Oxygen Demand (COD) values ranged from 1.68 to 35.21 mg/L and exhibited a strong increasing trend with salinity. The lowest value was observed in freshwater conditions (T6; 0 ppt), while the highest values occurred in marine and high-salinity areas (e.g., T1 and T2). This pattern suggests that organic matter accumulates in brackish to marine environments, potentially due to hydrodynamic conditions, sediment resuspension, and aquaculture-related inputs. The strong positive relationship highlights the role of salinity in influencing organic matter distribution. COD values below 25 mg/L are generally indicative of relatively good water quality, whereas higher values suggest moderate to strong organic pollution [10].

In general, elevated ammonia concentrations, imbalanced phosphate levels, and increased COD values are widely recognized indicators of water quality deterioration in aquatic systems, as they are associated with increased organic loading, eutrophication processes, and potential toxicity to aquatic organisms. Furthermore, water quality standards for both aquaculture and aquatic ecosystems indicate that elevated levels of reduced nitrogen (TAN) and organic matter (as reflected by COD) beyond optimal thresholds are indicative of degraded water conditions [9].

The degradation of water quality in coastal areas is generally closely associated with high nutrient loads originating from land-based sources. Anthropogenic activities such as agriculture, domestic wastewater discharge, and industrial effluents contribute to increased inputs of nitrogen and phosphorus into water bodies through riverine transport and surface runoff. This condition has been widely reported as a primary driver of eutrophication in coastal ecosystems, where excessive nutrient enrichment leads to alterations in ecosystem structure and a decline in water quality [11]. Furthermore, in tropical regions, terrigenous nutrient inputs are considered a dominant factor driving coastal ecosystem degradation, particularly due to the intensification of human activities in coastal zones [4].

These results are consistent with previous studies indicating that nutrient concentrations tend to be higher near land-based sources and decrease toward offshore areas due to mixing and dilution processes. Studies in estuarine systems have shown that riverine inputs from agricultural activities and other anthropogenic sources significantly increase nitrogen and phosphorus concentrations in coastal waters, particularly in the form of ammonia and dissolved organic phosphorus [4]. This pattern is consistent with the findings of the present study, where relatively high TAN concentrations were observed at locations with lower salinity, indicating a strong influence of terrestrial inputs.

In addition, elevated COD values observed at several locations indicate a substantial accumulation of organic matter in the source waters. This accumulation is generally derived from organic waste originating from domestic activities and aquaculture operations, which subsequently undergo decomposition and increase oxygen demand in the aquatic system. Such conditions may further deteriorate water quality and accelerate coastal ecosystem degradation through eutrophication and hypoxia processes [4].

These findings reinforce the understanding that water quality in traditional aquaculture systems is strongly influenced by external environmental conditions, particularly the quality of source water from coastal areas. Degradation occurring prior to water entering the pond system increases the management burden within aquaculture operations and may reduce production efficiency and long-term sustainability. Therefore, water quality management in traditional aquaculture cannot be addressed solely within the pond system, but must also consider upstream conditions and the broader dynamics of coastal ecosystems.

It should be noted that the present study was based on a single sampling campaign conducted during the rainy season (October 2025). Therefore, the observed nutrient concentrations and stoichiometric conditions represent a temporal snapshot of the study area and may not fully capture seasonal variability in coastal water quality. Increased freshwater inflow and hydrological flushing during the rainy season may contribute to nutrient dilution in coastal waters. Consequently, nutrient accumulation and water quality deterioration could potentially become more pronounced during the dry season, when river discharge and water exchange are reduced. Further seasonal monitoring is therefore necessary to better understand temporal nutrient dynamics and ecosystem variability in the coastal waters of Karawang Regency

3.2 Carbon–Nitrogen Ratio (C/N) and Nitrogen–Phosphorus Ratio (N/P)

As shown in Table 2, C-organic concentrations ranged from 0.56 to 11.74 mg L^{-1}, while total nitrogen (TN) ranged from 4.85 to 9.32 mg L^{-1} across sampling locations in Karawang Regency. The relatively higher TN values compared to C-organic indicate an imbalance between carbon and nitrogen availability. Consequently, the C/N ratio ranged from 0.10 to 2.30 and remained consistently low across all sites. In Figure 3, a slight increasing trend in the C/N ratio with salinity can be observed, however values remained within a narrow and low range throughout the study area.

The results of this study indicate that the C/N ratio in source waters used for traditional aquaculture ponds in Karawang Regency is consistently low (0.10–2.30), suggesting carbon limitation relative to nitrogen. This condition has important implications for microbial activity and biogeochemical processes in aquatic systems, particularly those related to the nitrogen cycle [12]. Generally, balanced and productive estuarine or coastal ecosystems exhibit moderate C/N ratios ranging between approximately 6 and 10, which reflect relatively stable nutrient cycling and sufficient carbon availability to support microbial decomposition and nitrogen transformation processes [12]. For aquatic ecosystem management, maintaining a more balanced C/N ratio is considered important to support efficient microbial nutrient recycling and overall ecological stability. In aquaculture systems, C/N ratios between 10 and 20 are often regarded as favorable for promoting heterotrophic bacterial assimilation of inorganic nitrogen and improving water quality [13]. Therefore, the extremely low C/N ratios observed in this study indicate that the ecosystem is likely under strong nitrogen pressure and may experience limited natural nitrogen removal capacity.

The C/N ratio in aquatic systems is a key factor controlling the growth and activity of heterotrophic microorganisms. Heterotrophic microbes require organic carbon as an energy source and nitrogen as a nutrient for biomass synthesis. When the C/N ratio is low, carbon availability becomes a limiting factor for microbial growth, thereby constraining nitrogen assimilation by microorganisms [13]. As a consequence, dissolved nitrogen forms, such as ammonia and nitrate, tend to persist in the water column rather than being effectively incorporated into microbial biomass.

Carbon limitation also influences the balance of processes within the nitrogen cycle. Under low C/N conditions, nitrification tends to be more dominant than denitrification. Nitrification is the oxidation of ammonia to nitrate by autotrophic bacteria that do not rely on organic carbon, whereas denitrification requires organic carbon as an electron donor. Therefore, carbon limitation can inhibit denitrification, a process that removes nitrogen from the system in the form of gaseous nitrogen (N_2)[10]. As a result, this condition may lead to the accumulation of dissolved inorganic nitrogen in the water column.

Furthermore, low C/N ratios have been widely associated with increased nitrogen accumulation in various aquatic systems, including coastal waters and aquaculture ponds. Studies have shown that carbon-limited systems tend to exhibit low efficiency in converting nitrogen into microbial biomass, resulting in nitrogen remaining in dissolved forms and potentially increasing the risk of eutrophication [3]. In the context of aquaculture ponds, this condition may further deteriorate water quality through the accumulation of toxic nitrogen compounds, such as ammonia. Therefore, low C/N ratios in source waters not only reflect nutrient imbalance but also have direct implications for the efficiency of microbial nitrogen utilization and the potential accumulation of nitrogen within the system.

Table 2. Concentrations of C-organic, total nitrogen (TN), phosphate (PO_4^{3-}–P), and derived nutrient ratios (C/N and N/P) across sampling locations.

Location	Salinity (ppt)	C-Organic (mg L^{-1})	TN (mg L^{-1})	PO_4^{3-}-P (mg L^{-1})	C/N	N/P
T1	23	11.74	5.72	0.01	2.05	953.38
T2	30	11.74	6.44	0.05	1.82	126.30
T3	5	6.52	5.38	0.18	1.21	30.22
T4	15	9.11	5.33	0.04	1.71	124.06
T5	16	5.60	9.32	0.24	0.60	38.71
T6	0	0.56	5.43	0.22	0.10	24.90
T7	14	3.60	6.12	0.09	0.59	68.77
T8	5	1.40	4.85	0.13	0.29	36.50
T9	20	11.20	4.87	0.29	2.30	16.61

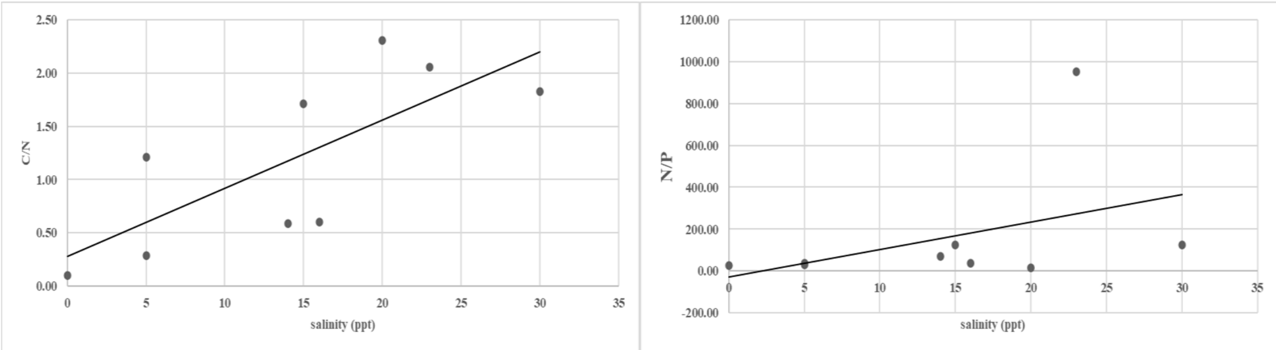

Fig. 3. Relationship between salinity and nutrient ratios: (a) C/N ratio and (b) N/P ratio in water sources used for traditional aquaculture in Karawang Regency. Dotted lines indicate linear regression trends.

Total nitrogen (TN) concentrations (4.85–9.32 mg L^{-1}) were consistently higher than phosphate (PO_4^{3-}–P), which ranged from 0.018 to 0.898 mg L^{-1}. This disparity is reflected in the N/P ratio, which varied widely from 16.61 to 953.38. Most locations exhibited relatively high N/P values, with an increasing tendency along the salinity gradient as shown in the graphical analysis (Figure 3). The extremely high N/P ratio observed at certain locations highlights a strong imbalance between nitrogen and phosphorus levels across the study area.The results of this study indicate that the N/P ratio in source waters used for traditional aquaculture ponds in Karawang Regency is extremely high (16.61–953.38), reflecting a strong imbalance between nitrogen and phosphorus. N/P values that substantially exceed the classical Redfield ratio (16:1) suggest that phosphorus acts as the primary limiting nutrient in this aquatic system [14].

Phosphorus limitation has direct implications for primary productivity, particularly affecting the growth of phytoplankton and microalgae. Under conditions where nitrogen is relatively abundant but phosphorus is limited, the growth rate of photosynthetic organisms is constrained, as phosphorus is an essential component in the formation of ATP, nucleic acids, and cellular membranes. Several studies have shown that phosphorus limitation can reduce photosynthetic efficiency and biomass production, even when nitrogen availability is high [14].

On the other hand, high N/P ratios also increase the risk of imbalanced eutrophication. In systems characterized by excess nitrogen and phosphorus limitation, even small increases in phosphorus availability—such as those resulting from sediment resuspension or external inputs—can rapidly trigger algal blooms. These events are often unstable and may lead to sharp fluctuations in water quality, including declines in dissolved oxygen due to the decomposition of algal biomass [1].

Furthermore, imbalanced N/P ratios reflect disproportionate anthropogenic pressures on nutrient cycling. Nitrogen inputs from land-based sources, such as agricultural runoff and domestic wastewater, are typically higher than phosphorus inputs, thereby reinforcing nutrient imbalances in coastal waters [1]. This pattern is consistent with the findings of the present study, where nitrogen was relatively abundant while phosphorus remained limited and variable. Therefore, high N/P ratios not only indicate phosphorus limitation but also signal potential instability in aquatic ecosystems. This condition represents an important consideration for water quality management, as nutrient imbalances can influence biological productivity and increase the risk of environmental disturbances such as eutrophication.

The combined analysis of C-organic, total nitrogen (TN), phosphate (PO_4^{3-}–P), and their derived ratios revealed an imbalance in C–N–P stoichiometry across the sampling locations in Karawang Regency.

Degraded source water quality, together with nutrient imbalances characterized by low C/N and high N/P ratios, has direct implications for the sustainability of traditional aquaculture systems in Karawang Regency. One of the primary risks is the increased potential toxicity of reduced nitrogen compounds, particularly ammonia (NH_3/NH_4^+) and nitrite (NO_2^-), which are known to be harmful to aquatic organisms. Elevated ammonia concentrations, especially in the un-ionized form (NH_3), can cause physiological stress, reduced growth, and even mortality in fish and shrimp [12]. Meanwhile, nitrite can interfere with the oxygen-carrying capacity of blood (methemoglobinemia), leading to hypoxic conditions in cultured organisms [9].

In addition to toxicity risks, nutrient imbalance also contributes to reduced production efficiency in traditional aquaculture systems. Low C/N ratios reflect a limitation of organic carbon, which plays a crucial role in supporting the growth of heterotrophic microorganisms. These microbes are responsible for nutrient recycling and for assimilating inorganic nitrogen into more stable biomass, which can subsequently serve as a natural food source (e.g., klekap) for cultured organisms. When carbon availability is limited, the efficiency of nitrogen utilization declines, causing nitrogen to accumulate in dissolved forms that may be detrimental to the system [11]. This condition can lead to unstable water quality and reduced aquaculture performance, both in terms of growth and survival rates of cultured organisms.

Furthermore, traditional aquaculture systems generally have limited capacity for water quality management, including minimal use of aeration, low control over nutrient inputs, and a high dependence on natural water quality from the surrounding environment. These limitations make the system more vulnerable to fluctuations in water quality and the accumulation of harmful compounds. In contrast to intensive systems, which allow tighter control over environmental parameters, traditional ponds are often unable to compensate for degraded source water conditions [2]. Therefore, the combination of poor source water quality and limited internal management capacity may exacerbate environmental conditions within the culture system. This highlights the importance of adopting a management approach that not only focuses on in-pond practices but also considers source water quality as a key determinant of the success of traditional aquaculture systems.

3.3 Evaluation Based on TLA

As shown in Table 3, the Traffic Light Approach (TLA) evaluation demonstrated a predominance of red and yellow classifications across most water quality parameters in Karawang Regency. Total Ammonia Nitrogen (TAN) was predominantly classified as red in the majority of sampling locations, with only a few sites showing green or yellow conditions. Similarly, phosphate (PO_4^{3-}) exhibited a strong dominance of red classification, indicating consistently poor status across several locations.

Chemical Oxygen Demand (COD) also showed a considerable number of red classifications, particularly in freshwater and high-salinity conditions, while only a limited number of locations were categorized as green. Nitrite (NO_2^-) displayed more variability, with most locations classified as green, although some yellow categories were still observed. In contrast, nitrate (NO_3^-) was generally classified as yellow, indicating moderate conditions across the study area.

Total nitrogen (TN) was predominantly classified as yellow, with occasional red classifications, suggesting relatively stable but moderate conditions. The C/N ratio was consistently classified as red across all sampling locations, indicating uniformly low values, while the N/P ratio showed mixed classifications, ranging from red to green, reflecting substantial variability among sites.

Overall, as shown in Table 3 the TLA-based evaluation indicates that TAN, phosphate, COD, and C/N ratio are the most critical parameters, as they are frequently associated with poor (red) status across the sampling locations

Table 3. Traffic Light Approach (TLA) classification of water quality parameters and nutrient ratios based on scoring values in water sources used for traditional aquaculture in Karawang Regency.

Location	TAN	NO_2^-	NO_3^-	PO_4^{3-}	COD	TKN	C/N	N/P
T1	0.06 (R)	6.67(Y)	4.23 (Y)	6.05 (Y)	2.46 (R)	5.42(Y)	2.05 (R)	1.00 (R)
T2	7.97(G)	9.80 (G)	3.89 (Y)	4.30 (Y)	2.46 (R)	3.95 (Y)	1.82 (R)	1.00 (R)
T3	7.03 (G)	8.93 (G)	4.38 (Y)	0 (R)	5.22 (Y)	5.82 (Y)	1.21 (R)	4.00 (Y)
T4	3.65 (Y)	8.96 (G)	4.94 (Y)	4.60 (Y)	3.77 (Y)	5.00 (Y)	1.71 (R)	1.00 (R)
T5	0.00 (R)	9.11 (G)	2.36 (R)	0 (R)	6.60 (Y)	0 (R)	0 (R)	4.00 (Y)
T6	0.00(R)	6.01 (Y)	5.17 (Y)	0 (R)	1.68 (R)	4.80 (Y)	0 (R)	7.00 (G)
T7	5.99 (Y)	10(G)	5.63 (Y)	2.84 (R)	9.60 (G)	2.50 (R)	0 (R)	1.00 (R)
T8	1.85 (R)	9.83(G)	9.81 (G)	1.15 (R)	4.2 (Y)	3.32 (Y)	0 (R)	4.00 (Y)
T9	1.02 (R)	10(G)	6.00 (Y)	0 (R)	2.73 (R)	5.42 (Y)	2.30 (R)	10.00 (G)

Note: Values are presented as score (0–10) followed by TLA classification in parentheses: R = red (poor), Y = yellow (moderate), G = green (good)

Figure 4 shows the distribution of water quality sustainability status based on the Traffic Light Approach (TLA). The analysis indicates that most parameters were classified in the red category (43.06%), suggesting that water quality conditions are still insufficient to support sustainable aquaculture practices. Furthermore, 38.89% of the parameters were categorized as yellow, indicating moderate conditions that require attention, while only 18.06% were classified as green, representing good conditions. These findings suggest that the water quality in traditional ponds is still dominated by suboptimal conditions, highlighting the need for more effective management strategies to improve sustainability status.

The results of this study indicate that the quality of source water used in traditional aquaculture ponds in Karawang Regency has already been degraded prior to entering the pond system. This is reflected in the dominance of red and yellow classifications for several key parameters, including Total Ammonia Nitrogen (TAN), phosphate (PO_4^{3-}), and Chemical Oxygen Demand (COD), indicating moderate to poor water quality conditions [10].

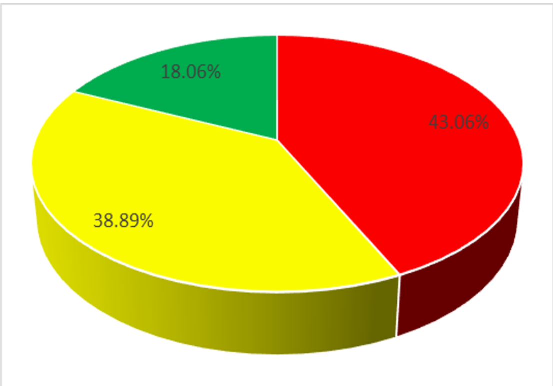

Fig. 4. Distribution of water quality sustainability status based on the Traffic Light Approach (TLA)

3.4. Management Implications

The results of this study indicate that nutrient imbalance—characterized by low C/N ratios and high N/P ratios—has important implications for water quality management strategies in traditional aquaculture systems in Karawang Regency. These findings highlight that water quality management should not rely solely on controlling individual parameters, but must also consider the stoichiometric balance among carbon (C), nitrogen (N), and phosphorus (P). Nutrient ratio–based approaches have been widely recognized as a more comprehensive framework for understanding biogeochemical dynamics and for designing effective management interventions [14].

Low C/N ratios indicate a limitation of organic carbon, which plays a critical role in supporting the activity of heterotrophic microorganisms, particularly in the assimilation of inorganic nitrogen. Under such conditions, increasing carbon availability becomes a key strategy to improve nitrogen utilization efficiency, reduce the accumulation of dissolved nitrogen compounds, and stabilize water quality. The addition of external carbon sources has been shown to increase the C/N ratio, stimulate microbial biomass growth, and convert inorganic nitrogen into more stable and less toxic forms [12, 13]. Thus, this approach not only functions as a nutrient control mechanism but also has the potential to enhance system productivity through the development of microbial-based natural food sources.

On the other hand, high N/P ratios indicate phosphorus limitation, which may affect the stability of primary productivity. Although direct phosphorus intervention must be carefully managed to avoid the risk of eutrophication, integrated nutrient management through balancing nutrient ratios is considered a more effective approach than partial manipulation of individual parameters [1].

In this context, the use of biochar as a potential carbon source represents a promising management alternative. Biochar may functions not only as a carbon provider but also as a material with adsorptive properties that can facilitate nutrient retention and providing habitat for microorganisms that involved in nutrient cycling. Previous studies have demonstrated that biochar application in aquatic and soil systems can enhance nutrient retention capacity, improve stoichiometric balance, and support microbial activity involved in nutrient cycling [15]. However, further studies under local traditional aquaculture conditions are still required to evaluate its effectiveness, feasibility, and practical applicability for sustainable aquaculture management

4. Conclusion

Coastal water quality in Karawang Regency exhibits a clear C–N–P stoichiometric imbalance, characterized by low C/N ratios and high N/P ratios. This condition indicates that the source water is not yet optimal for use in traditional aquaculture systems, as it may promote nitrogen accumulation and destabilize nutrient dynamics. A nutrient ratio–based approach provides more comprehensive insights than single-parameter evaluation, particularly in identifying carbon and phosphorus limitations within aquatic systems. Therefore, water quality management should adopt a more integrated framework that considers nutrient balance as a fundamental basis for decision-making. Management interventions aimed at improving carbon availability may represent a potential strategy to enhance nutrient balance, improve nitrogen utilization efficiency, and support more stable water quality conditions in traditional aquaculture systems.

The authors would like to express their sincere gratitude to IPB University, particularly the Natural Resources and Environmental Management (NREM) program, for academic support. The authors also acknowledge the Ministry of Marine Affairs and Fisheries of the Republic of Indonesia (KKP), especially the Directorate General of Aquaculture, the Aquaculture Production Service Center (BLUPPB) Karawang, and Center for Marine and Fisheries Education, for their support and facilitation during this study.

References

1. Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., Lancelot, C., Likens, G.E.: Controlling Eutrophication : Nitrogen and Phosphorus. Policy Forum. 323, (2009)
2. Boyd, C.E., Tucker, C.S.: Pond Aquaculture Water Quality Management. Springer Science+Business Media, New York (1998)
3. Paerl, H.W., Otten, T.G.: Harmful Cyanobacterial Blooms : Causes , Consequences , and Controls. Environ. Microbiol. (2013). https://doi.org/10.1007/s00248-012-0159-y
4. Adyasari, D., Pratama, M.A., Teguh, N.A., Sabdaningsih, A., Kusumaningtyas, M.A., Dimova, N., Adhiraga, M., Andriany, N., Sabdaningsih, A., Astrid, M., Dimova, N., Pratama, M.A., Teguh, N.A., Sabdaningsih, A., Kusumaningtyas, M.A., Dimova, N.: Anthropogenic impact on Indonesian coastal water and ecosystems : Current status and future opportunities. Mar. Pollut. Bull. 171, 112689 (2021). https://doi.org/10.1016/J.MARPOLBUL.2021.112689
5. Sachoemar, S.I., Yanagi, T.: Seasonal variation in water quality at the northern coast of Karawang. La Mer. 37, (1999)
6. Sterner, R.W., Elser, J.: Ecological Stoichiometry : Overview. Encycl. Ecol. (2008). https://doi.org/10.1016/B978-008045405-4.00309-8
7. APHA: Standard Methods for the Examination of Water and Wastewater. American Public Health Association, American Water Works Association, Water Environment Federation (2017)
8. Tchobanoglous, G., Burton, F.L., Stensel, H.D.: Wastewater Engineering: Treatment and Reuse. Metcalf&Eddy Inc. (2003)
9. Hargreaves, J.A.: Nitrogen biogeochemistry of aquaculture ponds. Aquaculture. 166, 181–212 (1998)
10. Boyd, C.E.: Water Quality An Introduction. Springer, New York (2015)
11. Stutter, M.I., Graeber, D., Evans, C.D., Wade, A.J., Withers, P.J.A.: Science of the Total Environment Balancing macronutrient stoichiometry to alleviate eutrophication. Sci. Total Environ. 634, 439–447 (2018). https://doi.org/10.1016/j.scitotenv.2018.03.298
12. Avnimelech, Y.: Carbon/nitrogen ratio as a control element in aquaculture systems. Aquaculture. 176, 227–235 (1999). https://doi.org/http://dx.doi.org/10.1016/S0044-8486(99)00085-X
13. Crab, R., Defoirdt, T., Bossier, P., Verstraete, W.: Biofloc technology in aquaculture : Beneficial effects and future challenges. Aquaculture. 356–357, 351–356 (2012). https://doi.org/10.1016/j.aquaculture.2012.04.046
14. Redfield, A.C.: The Biological Control of Chemical Faktors in The Environment. Am. Sci. 46, 205–221 (1958)
15. Tan, X., Liu, Y., Zeng, G., Wang, X., Hu, X., Gu, Y., Yang, Z.: Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere. 125, 70–85 (2015). https://doi.org/10.1016/j.chemosphere.2014.12.058