

Environmental assessment of shrimp farming in coastal Tamil Nadu of India: a case study of Nagapattinam and Mayiladuthurai districts

¹Lloyd C. Christy, ²Aruna Satyapriyan, ³Selvaraj Sethu, ¹Ilangamani Paramasivan, ³Dinesh Rajan, ¹Agnes D. A. Sam, ¹Manimaran Rasappan, ¹Shweta Biswas, ¹Omprakash Pandian, ¹Sarabes Nagendramani

¹ Department of Fisheries Extension, Economics and Statistics, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri, India; ² Department of Aquatic Environment Management, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri, India; ³ Department of Aquaculture, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri, India.
Corresponding authors: L. C. Christy, lloyd@tnfu.ac.in; D. Rajan, dinesh@tnfu.ac.in

Abstract. Shrimp aquaculture is a major economic activity in Tamil Nadu, with the Nagapattinam and Mayiladuthurai districts together accounting for nearly 45% of the state's licensed shrimp farms. Although the sector has periodically attracted concern regarding its environmental sustainability particularly with respect to shrimp farm discharge water quality and coastal ecosystem health there remains a paucity of empirical, field-based assessments from this region. The present study evaluated key environmental parameters across twelve shrimp farms and two control sites located in Nagapattinam and Mayiladuthurai districts. Water quality and plankton composition were assessed during the summer and pre-monsoon seasons, with samples collected from intake waters, farm discharge points, discharge-receiving areas, and control sites. Physico-chemical parameters including ammonia, nitrite, nitrate, and chemical oxygen demand (COD) were analysed and compared against regulatory standards prescribed by the Coastal Aquaculture Authority (CAA) and the Tamil Nadu Pollution Control Board (TNPCB). Statistical analyses were conducted using one-way ANOVA and independent t-tests to examine spatial and seasonal variations in water quality ($p < 0.05$). Results indicated no significant differences in most parameters among the different water types, with only localized increases in COD ($p < 0.001$) observed values that nonetheless remained well within permissible limits. Plankton analysis revealed diatom dominance and diverse zooplankton assemblages, suggesting ecological stability in the receiving environments. Overall, the findings demonstrate that shrimp farming practices in the study areas are environmentally compliant and exert minimal ecological impact, thereby reinforcing the sector's sustainability and its continued importance as a source of rural livelihood and economic growth in coastal Tamil Nadu.

Keywords: coastal Tamil Nadu, discharge water, plankton composition, shrimp farming, water quality.

Introduction. Frozen shrimp continues to be the major export commodity from India in terms of both quantity and value, accounting for 40.19% of total export quantity and 66.12% of total export earnings. During 2023-2024, India exported 716,004 MT of frozen shrimp, valued at US\$ 4,881.27 million. Among the exported species, Pacific white shrimp *Penaeus vannamei* dominated, with exports increasing marginally by 0.33% in quantity, from 623,432 MT to 625,475 MT (MPEDA, 2024). Tamil Nadu, which possesses the second-longest coastline in India, is well endowed with natural resources suitable for coastal aquaculture. The state has an estimated 56,000 hectares of brackish water resources, of which approximately 8,600 hectares are currently utilised for *P. vannamei* culture. The average productivity of *P. vannamei* shrimp farming in Tamil Nadu is reported to be around 5.20 MT ha⁻¹ year⁻¹ (Angela & Sharma, 2023). Shrimp farming has emerged as a significant economic activity across the thirteen coastal districts of Tamil Nadu. The sector experienced rapid expansion during the 1990s, followed by a decline in the early 2000s due to disease outbreaks, indiscriminate use of chemicals, and the

widespread damage caused by the 2004 Indian Ocean tsunami. Subsequently, the industry witnessed a revival during the 2010s, largely driven by the introduction and adoption of *P. vannamei*, which offered improved growth performance and production stability (Pratheepa et al., 2023).

Among the coastal districts of Tamil Nadu, Nagapattinam and Mayiladuthurai play a prominent role in shrimp farming. Of the 2,404 shrimp farms operating in the state, 1,072 farms are located within these two districts, together accounting for 44.59% of the Coastal Aquaculture Authority (CAA) licensed shrimp farms in Tamil Nadu (CAA, 2025). In addition, the districts collectively possess approximately 19,600 hectares of brackish water resources, highlighting their significance in the state's shrimp aquaculture sector. Water source pollution has emerged as a major global environmental concern, posing risks to both aquatic ecosystems and human health (Mustafa et al., 2024). Shrimp farming is among the most water-intensive aquaculture practices, generating substantial volumes of discharge water. When inadequately managed, shrimp farm discharges can adversely affect receiving water bodies (Cargnin & João, 2024). The principal environmental concern associated with shrimp farming arise from discharge water release during routine water exchange and harvesting operations. Such discharges often contain elevated levels of nutrients, suspended solids, and organic matter, which may lead to reduced dissolved oxygen concentrations and increased turbidity in adjacent aquatic environments (Bull et al., 2021).

Despite these concerns, shrimp farming plays an important role in rural livelihoods in Tamil Nadu, supporting employment across a wide range of skill levels and contributing to household incomes, food production, and reduced rural-urban migration. Although the sector has occasionally faced legal challenges primarily arising from regulatory ambiguities such issues have largely been addressed through policy clarification and due legal processes, underscoring the continued relevance of shrimp farming in rural development. In response to the rapid expansion of coastal aquaculture and its potential environmental and social implications, the CAA was established in 2005 to regulate shrimp farming activities and to frame science-based guidelines, drawing on lessons learned from earlier environmental and social challenges (Maity et al., 2021). In parallel, the Tamil Nadu Pollution Control Board (TNPCB) plays a critical role in monitoring and enforcing environmental standards, ensuring that shrimp farms comply with prescribed discharge water norms and environmental safeguards. To date, however, the environmental assessment of shrimp farming have not been comprehensively evaluated, with only a limited number of studies conducted by institutions such as the CSIR-National Environmental Engineering Research Institute (NEERI). The limited availability of region-specific empirical evidence has contributed to ongoing debates regarding the sector's environmental performance. Against this backdrop, there is a clear need for systematic field-based investigations, and the present study aims to assess the environmental implications of selected shrimp farms in the Nagapattinam and Mayiladuthurai districts of Tamil Nadu.

Material and Method

Study sites and sampling plan. The coastal districts of Mayiladuthurai and Nagapattinam in Tamil Nadu were selected for the study due to the high concentration of shrimp farming activities in these areas. A total of twelve shrimp farms (Figure 1) were purposively selected, ensuring adequate geographical representation within each district. Two spatial clusters were identified in each district, resulting in four clusters, with six shrimp farms selected per district. In addition, two control sites were included in the study to provide reference conditions for comparison with the selected shrimp farms. Tharangambadi in Mayiladuthurai district was selected as a control site because the area does not support shrimp farming activities. In Nagapattinam district, Velankanni was included as the second control site, representing an area influenced by external anthropogenic activities, particularly sewage sources. These two sites were included to provide reference conditions for assessing the water-quality characteristics of the shrimp farm areas. Water samples from the control sites were collected during the summer and

pre-monsoon seasons using the same sampling and analytical procedures followed for the selected shrimp farms. Water samples from both sites were collected during the summer and pre-monsoon crop seasons and analysed using the same standard procedures applied to the selected shrimp farms. Sampling included intake water, discharge water, discharge-receiving water, and control site water, along with plankton samples from shrimp pond waters. All samples were collected at weekly intervals from February to November 2024. Laboratory analyses were carried out following the procedures outlined in the Standard Methods for the Examination of Water and Wastewater (APHA, 2017).

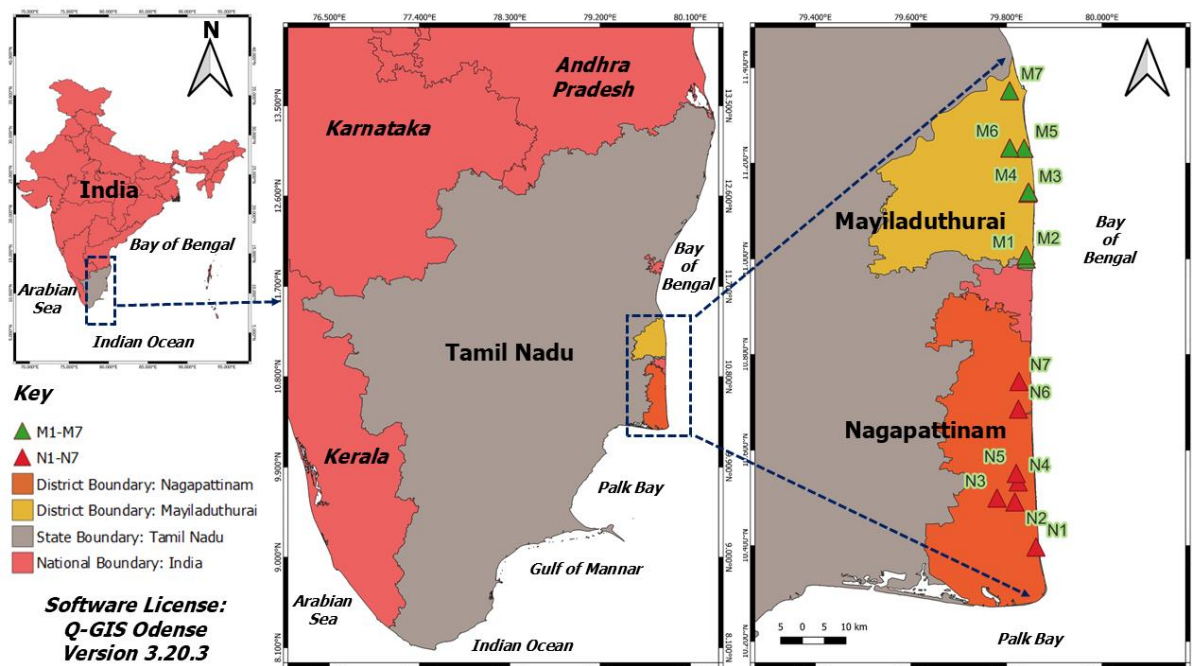


Figure 1. Map of the study area showing the distribution of the 14 (12 farms and 2 control sites) selected sampling locations in Nagapattinam and Mayiladuthurai districts.

Water quality and plankton analysis. Water samples were collected weekly during the summer and pre-monsoon seasons from four sampling locations: shrimp farm intake waters, pond discharge outlets, discharge-receiving waters adjacent to the farms, and a control site at Tharangambadi. Surface water samples were collected in pre-cleaned polyethylene bottles and brought to the laboratory, chilled for analysis. The indicators chosen were ammonia, nitrite, nitrate and chemical oxygen demand (COD), which are associated with nutrient enrichment and organic pollution and can adversely affect aquatic organisms and ecosystem functioning. Excessive nitrogenous and organic discharges can exceed the natural assimilative capacity of aquatic systems, leading to nutrient enrichment, eutrophication, and ecological imbalance (Gonsch, 2021). Laboratory analyses were carried out by standard methods outlined by APHA (2017) via spectrophotometric and titrimetric methods. At the same time, samples of phytoplankton and zooplankton were taken by plankton nets of 20 μm and 60 μm mesh size, respectively and preserved in 4% buffered formalin. Samples were concentrated and studied with a compound microscope, with the lowest taxonomic level identification done with standard plankton identification keys to determine plankton composition

Statistical analysis. To assess spatial variations in water quality, one-way analysis of variance (ANOVA) was performed to determine statistically significant differences in the concentrations of the selected parameters among intake water, discharge water, and discharge-receiving water. A separate one-way ANOVA was conducted by including control site water along with the three farm-related water types, to evaluate the influence of shrimp farm discharges relative to a reference environment. To examine

seasonal variations, independent t-tests were used to compare parameter concentrations in intake water, discharge water, and discharge-receiving water between the pre-monsoon and summer crop seasons, using pooled data from both districts. A significance level of $p < 0.05$ was applied for all statistical analyses.

Results and Discussion. In the present study, ammonia, nitrite, nitrate, and COD were evaluated across four categories of water samples, namely intake water, discharge water, discharge-receiving water, and control site water, during the summer and pre-monsoon seasons. For each category, mean values were calculated using data obtained from Cluster I and Cluster II in both Nagapattinam and Mayiladuthurai districts. Subsequently, mean values from the two districts were pooled to derive an overall range for each water category. The observed values were compared with the permissible limits prescribed by the CAA and the TNPCB. The regulatory limits for the assessed water quality parameters are presented in Table 1.

Permissible limits (Sources: CAA 2025; TNPCB 2024)

Table 1

<i>Parameters (mg L⁻¹)</i>	<i>CAA</i>	<i>TNPCB</i>
Ammonia	0.5	5
COD	75	250
Nitrate	0.5	-

Note: No specific permissible limits for nitrite by CAA and TNPCB.

Ammonia. Ammonia (NH₃) in aquatic environments originates primarily from the excretion of aquatic organisms and the decomposition of organic matter and is known to be toxic to aquatic life. In natural systems, ammonia is assimilated by algae or biologically oxidised by microorganisms to nitrite and subsequently nitrate (Xu et al., 2021). In coastal aquaculture systems, ammonia is regarded as a key pollutant, particularly in shrimp farming operations where feed inputs and organic loading are relatively high (Cardoso-Mohedano et al., 2016). During the summer season, ammonia concentrations ranged from 0.058 to 0.123 mg L⁻¹ in intake water, 0.250 to 0.357 mg L⁻¹ in discharge water, and 0.103 to 0.161 mg L⁻¹ in discharge-receiving waters, while the control site recorded a lower value of 0.033 mg L⁻¹. Similarly, during the pre-monsoon season, ammonia concentrations in intake water (0.040-0.043 mg L⁻¹), discharge water (0.052-0.089 mg L⁻¹), and discharge-receiving waters (0.049-0.072 mg L⁻¹) were marginally higher than those observed at the control site (0.039 mg L⁻¹). These observations indicate limited ammonia accumulation in areas influenced by shrimp farm discharges. Across both seasons, ammonia concentrations remained well below the permissible limits prescribed by the TNPCB and were close to the stricter discharge standards of the CAA. One-way ANOVA comparing ammonia concentrations among intake, discharge, and discharge-receiving waters showed no statistically significant differences ($p = 0.196$), indicating relatively uniform ammonia levels across these water types. However, when the control site was included in the analysis, the ANOVA indicated a marginal, though not statistically significant, variation ($F = 2.812$; $p = 0.085$). Duncan's post-hoc test revealed that ammonia concentrations in discharge and discharge-receiving waters were significantly higher than those at the control site, suggesting localized increases associated with farm discharge water release.

Independent *t*-tests revealed seasonal differences in ammonia concentrations across the three water types. In Mayiladuthurai district, significant seasonal variation was observed in discharge water ($p = 0.008$) and discharge-receiving waters ($p = 0.004$). In Nagapattinam district, ammonia concentrations differed significantly between seasons in discharge water ($p = 0.001$) and intake water ($p = 0.035$), while no significant seasonal difference was detected in discharge-receiving waters ($p = 0.112$).

Overall, although ammonia levels remained within prescribed regulatory limits and spatial variation was limited, the results indicate a clear seasonal influence on ammonia concentrations. Ammonia levels were generally higher during the summer season across intake, discharge, and discharge-receiving waters, likely due to elevated temperatures

and increased organic loading, which reduce dilution capacity. Similar seasonal patterns have been reported by Nagaraju et al. (2023). The average ammonia concentrations for different water sample categories during the summer and pre-monsoon seasons are presented in Figure 2.

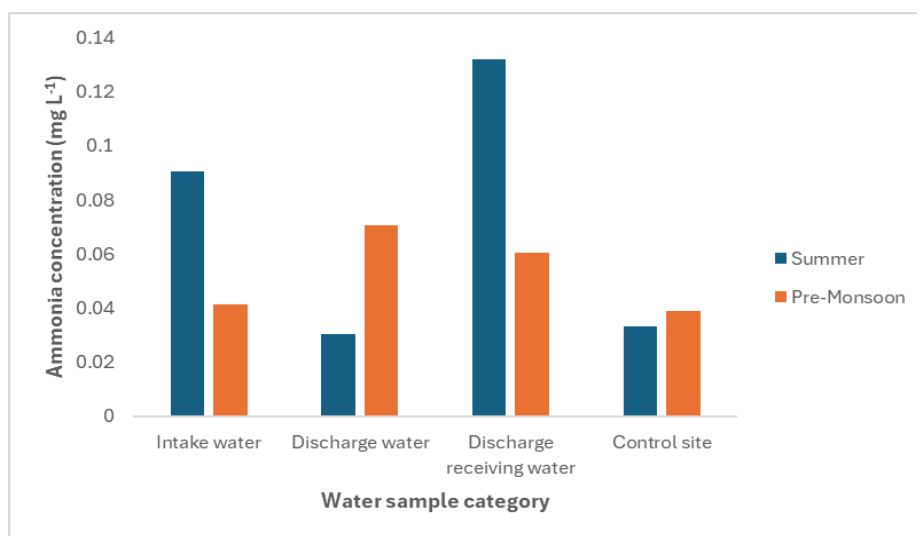


Figure 2. Average ammonia values of different water sample category (season-wise grouping).

Nitrite. Nitrite enters aquatic systems through anthropogenic activities such as industrial discharge, urban sewage, and aquaculture operations, and its presence is of concern due to its toxicity and interactions with other environmental stressors (Soares et al., 2020). Assessing nitrite concentrations along different stages of water use provides insight into potential sources and the extent of contamination. During the summer season, nitrite concentrations ranged from 0.030 to 0.031 mg L⁻¹ in intake water, 0.054 to 0.068 mg L⁻¹ in discharge water, and 0.031 to 0.038 mg L⁻¹ in discharge-receiving waters, with values marginally higher than those recorded at the control site (0.031 mg L⁻¹). A gradual increase from intake to discharge waters, with intermediate concentrations in the receiving waters, was observed, reflecting typical patterns during routine farm operations. In the pre-monsoon season, nitrite concentrations in intake water (0.041-0.048 mg L⁻¹), discharge water (0.020-0.046 mg L⁻¹), and discharge-receiving waters (0.029-0.046 mg L⁻¹) were again slightly higher than the control site (0.033 mg L⁻¹). Overall, the observed values indicate moderate nitrite levels consistent with regular farming activities and influenced by local environmental conditions. One-way ANOVA showed no significant differences in nitrite concentrations among intake, discharge, and discharge-receiving waters across both districts ($p = 0.474$). Similarly, when the control site was included, no significant differences were detected among the four water categories ($F = 1.227$; $p = 0.343$). Duncan's post-hoc test placed all water types within a single homogeneous subset, confirming the absence of statistically significant variation.

Independent *t*-test analysis revealed a significant seasonal difference in nitrite concentrations in discharge water of the Mayiladuthurai district ($p = 0.003$), indicating that seasonal factors such as variations in organic loading or temperature may influence nitrite accumulation in this zone. In contrast, no significant seasonal differences were observed in intake waters ($p = 0.256$) or discharge-receiving waters ($p = 0.452$), suggesting relatively stable nitrite levels in these components. In the Nagapattinam district, no significant seasonal differences were detected in discharge water ($p = 0.690$) or in intake and discharge-receiving waters in either district ($p > 0.05$), indicating overall seasonal stability. At present, no specific nitrite discharge standards have been prescribed by the TNPCB. Accordingly, the observed values were compared with thresholds reported in the literature. Although a few discharge water samples marginally exceeded the 0.06 mg L⁻¹ nitrite threshold suggested for the protection of coastal aquatic ecosystems (Moore, 1991), nitrite concentrations in intake and discharge-receiving waters remained within acceptable limits, indicating limited nitrite accumulation.

Comparable observations were reported by Priyadarsani & Abraham (2016), who documented low nitrite concentrations in inlet and outlet waters of shrimp farms operating under controlled management practices. The average nitrite concentrations for different water sample categories during the summer and pre-monsoon seasons are presented in Figure 3.

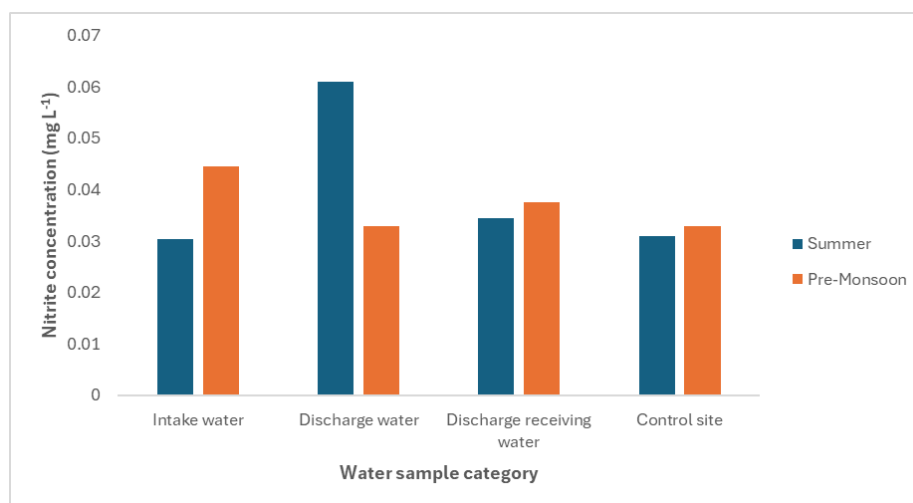


Figure 3. Average nitrite values of different water sample category (season-wise grouping).

Nitrate. Nitrate is an important pollutant due to its high solubility in water and its potential to cause eutrophication, posing risks to aquatic ecosystems and human health (Liu et al., 2022). Monitoring nitrate concentrations at different stages of water use provides insight into its accumulation and possible environmental impacts. During the summer season, nitrate concentrations ranged from 0.040 to 0.054 mg L⁻¹ in intake water, 0.082 to 0.114 mg L⁻¹ in discharge water, and 0.042 to 0.044 mg L⁻¹ in discharge-receiving waters, with values marginally higher than those recorded at the control site (0.051 mg L⁻¹). A moderate increase from intake to discharge waters was observed, while nitrate concentrations in discharge-receiving waters were comparatively lower. In the pre-monsoon season, nitrate concentrations in intake water (0.049-0.054 mg L⁻¹), discharge water (0.033-0.061 mg L⁻¹), and discharge-receiving waters (0.050-0.066 mg L⁻¹) were slightly lower than those at the control site (0.074 mg L⁻¹). Across both seasons, all observed nitrate concentrations remained well within the discharge standards prescribed by the CAA.

One-way ANOVA indicated no significant differences in nitrate concentrations among intake, discharge, and discharge-receiving waters across both districts ($p = 0.269$), suggesting relatively uniform nitrate levels among these water types. Similarly, when the control site was included, nitrate concentrations did not differ significantly among the four water categories (control, intake, discharge, and discharge-receiving) ($F = 1.263$; $p = 0.331$). Duncan's post-hoc test placed all water types within a single homogeneous subset, confirming the absence of statistically significant variation. Independent t -test analysis revealed a significant seasonal difference in nitrate concentrations in discharge water ($p = 0.001$) and intake water ($p = 0.005$) of the Mayiladuthurai district, indicating a seasonal influence on nitrate levels. However, no significant seasonal variation was observed in discharge-receiving waters ($p = 0.746$). In contrast, the Nagapattinam district showed no significant seasonal changes in nitrate concentrations in discharge ($p = 0.208$), intake ($p = 0.112$), or discharge-receiving waters ($p = 0.122$), indicating relatively stable nitrate dynamics across seasons. Overall, seasonal comparisons indicated that nitrate concentrations were slightly higher during the pre-monsoon season across intake, discharge, and discharge-receiving waters in both districts. The average nitrate concentrations for different water sample categories during the summer and pre-monsoon seasons are presented in Figure 4.

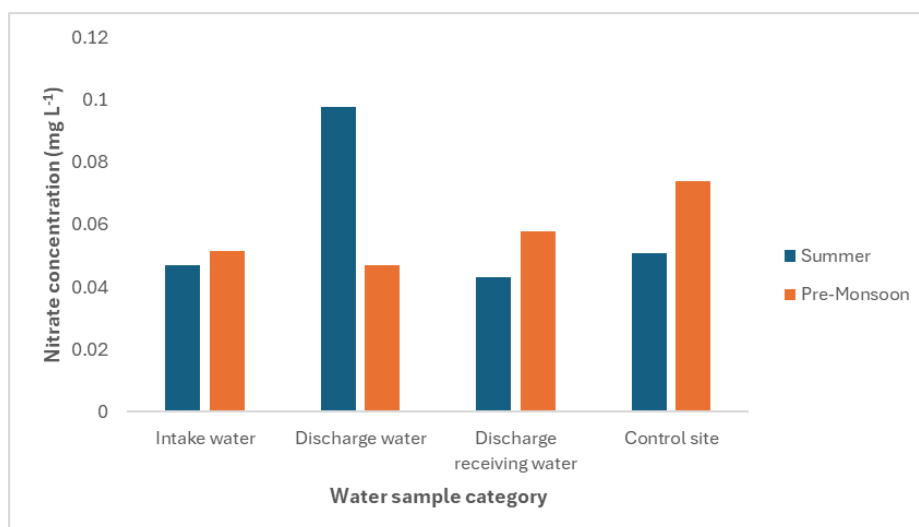


Figure 4. Average nitrate values of different water sample category (season-wise grouping).

COD. COD represents the concentration of oxidizable organic matter in water and is a key indicator of organic contamination. COD is closely associated with nutrient cycling and the presence of other environmental contaminants, making it a useful parameter for assessing organic enrichment in water bodies receiving shrimp farm discharge water (Lv et al., 2024). During the summer season, COD concentrations ranged from 63.67 to 69.70 mg L⁻¹ in intake water, 64.42 to 66.89 mg L⁻¹ in discharge water, and 61.83 to 65.57 mg L⁻¹ in discharge-receiving waters, all of which were higher than the control site value (31 mg L⁻¹). A slight increase from intake to discharge waters was observed; however, values remained within prescribed discharge limits. In the pre-monsoon season, COD concentrations in intake water (62.26-67.20 mg L⁻¹), discharge water (60.33-68.50 mg L⁻¹), and discharge-receiving waters (64.40-65.00 mg L⁻¹) were also higher than those at the control site (45 mg L⁻¹). Across both seasons, COD levels remained below the permissible limits prescribed by the TNPCB and were within or close to the stricter discharge standards of the CAA, indicating controlled organic loading associated with shrimp farming operations.

One-way ANOVA showed no significant differences in COD concentrations among intake, discharge, and discharge-receiving waters across both districts ($p = 0.810$), indicating comparable COD levels across these stages of water use. In contrast, COD concentrations differed significantly when control, intake, discharge, and discharge-receiving waters were analysed together ($F = 32.174$; $p < 0.001$). Duncan's post-hoc test placed the control water (mean COD = 38.00 mg L⁻¹) in a distinct subset, separate from intake, discharge, and discharge-receiving waters (mean COD $\approx$ 64-66 mg L⁻¹), indicating localized organic enrichment associated with shrimp farming, while remaining within prescribed environmental limits. Independent t -test analysis indicated no significant seasonal differences in COD concentrations across discharge water (Mayiladuthurai: $p = 0.063$; Nagapattinam: $p = 0.360$), discharge-receiving waters ($p = 0.824$; $p = 0.122$), and intake water ($p = 0.769$; $p = 0.661$) in either district. Overall, the results suggest a stable COD profile across both spatial and seasonal scales, reflecting consistent management practices and uniform discharge characteristics. Although statistically non-significant, COD concentrations were marginally higher during the pre-monsoon season compared to the summer season. The average COD values for different water sample categories during the summer and pre-monsoon seasons are presented in Figure 5.

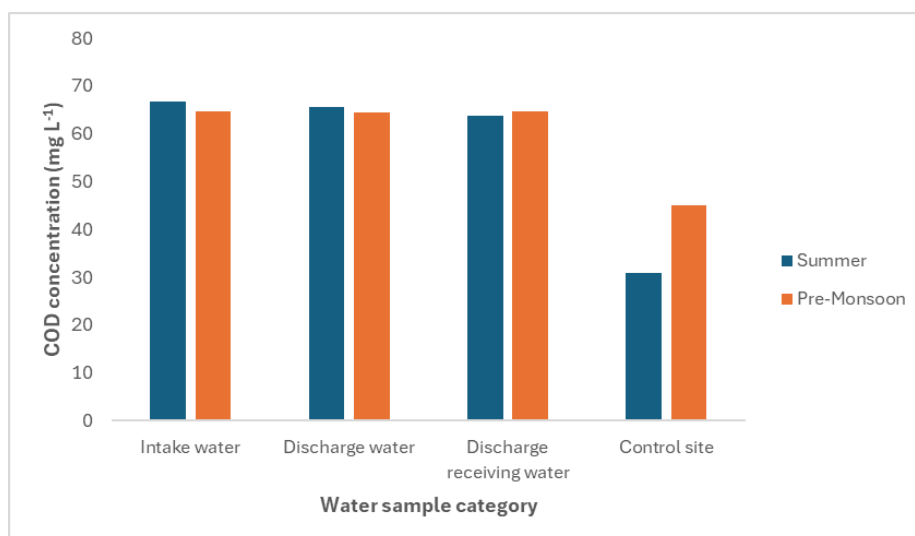


Figure 5. Average COD values of different water sample category (season-wise grouping).

Plankton analysis. Aquaculture wastewater often contains elevated nutrient loads that can alter the structure and functioning of adjacent aquatic ecosystems, particularly in the absence of sustainable management practices (Campos et al., 2021). Such nutrient enrichment may disrupt ecosystem balance by modifying phytoplankton community composition, while associated pollutants can disperse into surrounding water bodies. In addition, inputs from sewage and other anthropogenic sources can further elevate nutrient levels, potentially triggering bottom-up processes that favour the dominance of harmful or opportunistic algal species (Mahmudi et al., 2021). Plankton communities respond rapidly to changes in water quality, making them valuable indicators of environmental conditions. The presence or absence of specific phytoplankton and zooplankton taxa has therefore been widely used to assess the ecological status and overall health of aquatic systems (Chandel et al., 2024). In the present study, phytoplankton and zooplankton communities were analysed in selected clusters of Nagapattinam and Mayiladuthurai districts to evaluate ecological responses associated with shrimp farming activities.

Phytoplankton. Phytoplankton are a key component of aquatic ecosystems, and their abundance, species richness, and functional composition serve as important indicators of ecosystem health (Qu et al., 2022). Variations in phytoplankton assemblages often reflect changes in nutrient availability, pollution levels, and other environmental stressors, making them reliable indicators for water quality assessment. In the present study, diatoms were the dominant phytoplankton group across all sampling categories in both Mayiladuthurai and Nagapattinam districts. In Mayiladuthurai district, diatoms accounted for 37% at the control site, 35% in discharge-receiving waters, 37% in discharge waters, and 44% in pond waters. This group was followed by dinoflagellates (26-31%), blue-green algae (13-22%), and green algae (13-17%). The phytoplankton composition across different water samples in Mayiladuthurai district is presented in Figure 6. Similarly, in Nagapattinam district, diatoms remained dominant, with the highest proportion observed in discharge-receiving waters (46%), followed by pond waters (44%) and discharge waters (36%). Other phytoplankton groups included dinoflagellates (15-18%), green algae (18-21%), and blue-green algae (21-25%). The phytoplankton composition across different water samples in Nagapattinam district is shown in Figure 7.

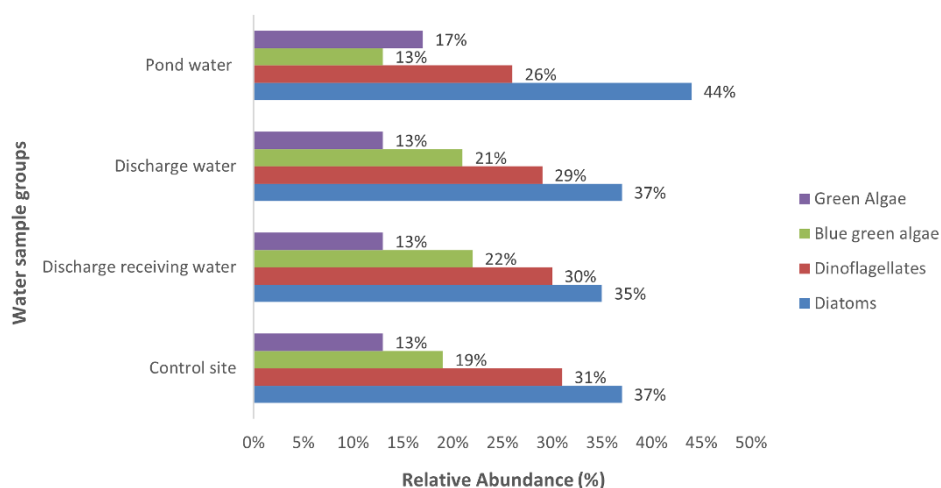


Figure 6. Phytoplankton composition of different water samples groups in Mayiladuthurai District.

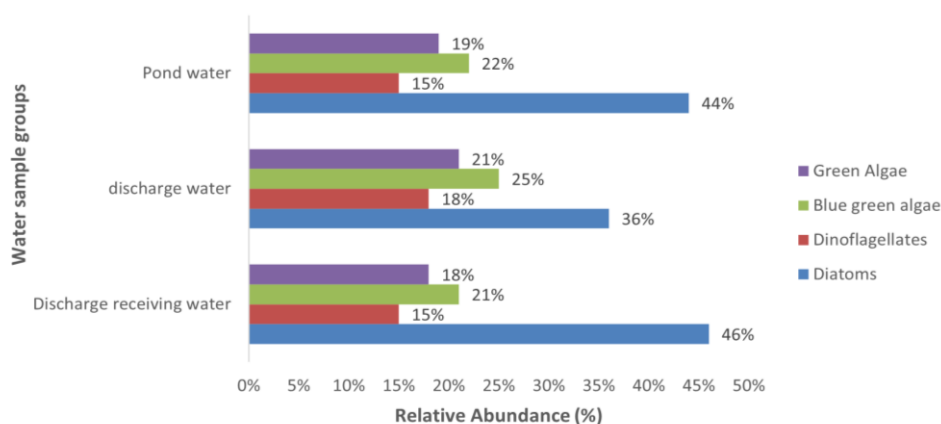


Figure 7. Phytoplankton composition of different water samples groups in Nagapattinam District.

Notably, blue-green algae (Cyanophyta) were more abundant in shrimp farm discharge waters than at the control site, suggesting localized nutrient enrichment associated with farm discharge water. Despite this increase, the consistent dominance of diatoms across all sampling locations indicates a relatively stable phytoplankton community structure, which is important for maintaining ecological balance. These observations are consistent with the findings of Campos et al. (2021), who reported higher abundances of Cyanophyta in shrimp ponds, positively correlated with orthophosphate concentrations, while adjacent estuarine waters characterised by lower nutrient levels and phytoplankton densities showed minimal influence from shrimp farm discharges. Collectively, these results suggest that although nutrient enrichment may favour certain phytoplankton groups within farm environments, the short-term ecological condition of adjacent estuarine waters remains largely unaffected, maintaining overall phytoplankton stability.

Zooplankton. Zooplankton communities serve as effective bioindicators of ecosystem health and water quality, as their community structure reflects both natural environmental variability and anthropogenic influences such as nutrient enrichment and pollution (Qi et al., 2025). In the Mayiladuthurai district, zooplankton composition varied among sampling sites. At the control site, rotifers were dominant (35%), followed by cladocerans (22%), copepods (17%), nauplii (13%), ostracods (9%), and mysis larvae (4%). In discharge-receiving waters, copepods formed the dominant group (20%), followed by insect larvae and nauplii (15% each), mysis larvae (13%), and rotifers, tintinnids, and dragonfly larvae (10% each), with cladocerans (7%) also contributing to community diversity. In discharge waters, cladocerans were most abundant (19%), followed by nauplii and mysis larvae (15% each), insect larvae and rotifers (12% each), copepods (11%), and dragonfly larvae and tintinnids (8% each). In pond waters, insect larvae, nauplii, and copepods were dominant (19% each), followed by dragonfly larvae

and mysis larvae (11% each), and tintinnids, cladocerans, and rotifers (7% each). The zooplankton composition across different water samples in Mayiladuthurai district is presented in Figure 8.

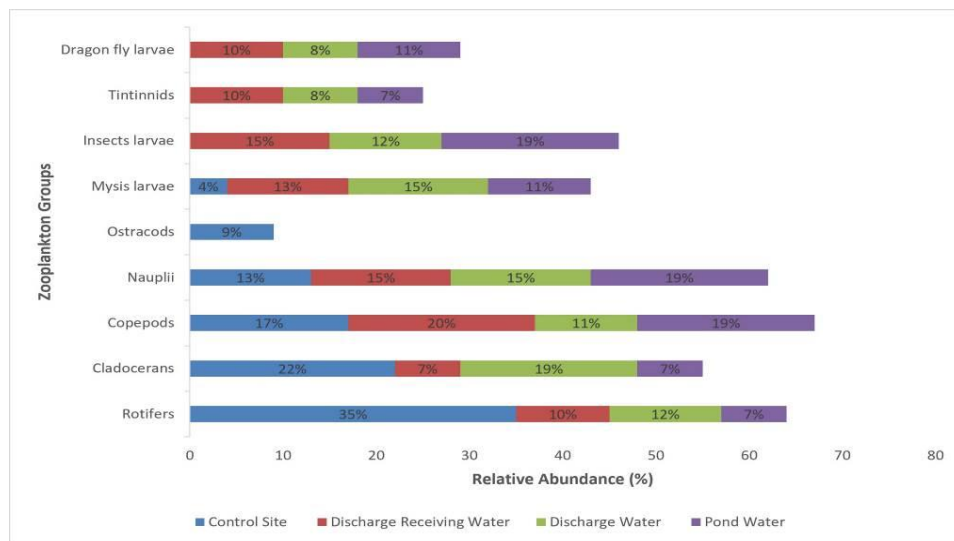


Figure 8. Zooplankton composition of different water samples category in Mayiladuthurai District.

In the Nagapattinam district, zooplankton assemblages also showed spatial variation. In discharge-receiving waters, cladocerans were dominant (20%), followed by insect larvae (18%), copepods (17%), tintinnids (15%), chaetognaths (12%), and rotifers and mysis larvae (9% each). In discharge waters, mysis larvae constituted the largest proportion (19%), followed by insect larvae and copepods (15% each), dragonfly larvae and rotifers (12% each), cladocerans (11%), and tintinnids and nauplii (8% each). In pond waters, nauplii were dominant (23%), followed by copepods (18%), rotifers and zoea larvae (14% each), cladocerans (13%), and decapod and mysis larvae (9% each). The zooplankton composition across different water samples in Nagapattinam district is shown in Figure 9.

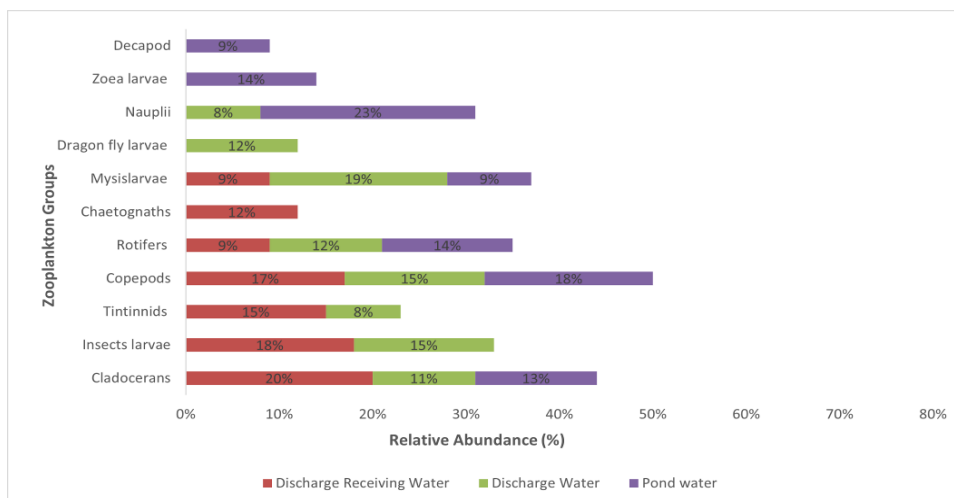


Figure 9. Zooplankton composition of different water samples category in Nagapattinam District.

Although copepods are widely regarded as indicators of good water quality, their reduced abundance at certain sites in the present study may reflect the influence of environmental stressors such as nutrient enrichment, pollution, and increased organic matter. This observation is consistent with the findings of Santos et al. (2021), who reported the continued dominance of copepods and rotifers across different aquatic environments and observed that shrimp farming discharge water did not produce significant short-term alterations in zooplankton community structure in a Neotropical

estuary. Taken together, these results suggest that variations in zooplankton assemblages are likely influenced more by broader environmental inputs and background pollution sources than by shrimp farm discharges alone.

Conclusions. The concentrations of ammonia, nitrite, and nitrate in shrimp farm discharge waters remained consistently within the regulatory limits prescribed by the CAA and the TNPCB, indicating a low risk of nutrient-driven impacts, including harmful algal blooms, in adjacent water bodies. Similarly, COD values were within acceptable limits, suggesting no significant potential for oxygen depletion in receiving environments. Phytoplankton analysis demonstrated a consistent dominance of diatoms across all shrimp farm discharge sites, reflecting stable ecological conditions. Although blue-green algae were present in higher proportions in discharge waters compared to control sites, their occurrence did not alter the overall phytoplankton community structure. Variations and reduced abundance of copepods at certain locations appeared to be influenced by multiple environmental factors, including inputs from domestic sewage and industrial activities unrelated to shrimp farming. One-way ANOVA revealed no significant differences in ammonia, nitrite, nitrate, and COD concentrations among intake, discharge, and discharge-receiving waters in both Mayiladuthurai and Nagapattinam districts ($p > 0.05$), indicating overall homogeneity in water quality across different stages of water use.

When the control site was included in the analysis, one-way ANOVA indicated no significant differences in nitrite and nitrate concentrations among the four water categories ($p > 0.05$), with Duncan's post-hoc test grouping all categories within the same homogeneous subset, indicating stable nutrient conditions across farming and non-farming areas. In the case of ammonia, ANOVA did not reach conventional levels of statistical significance ($p = 0.085$), whereas COD concentrations were significantly higher in intake, discharge, and discharge-receiving waters compared to the control site ($p < 0.001$), reflecting localized organic enrichment associated with shrimp farming activities and other anthropogenic inputs. Independent *t*-test analysis revealed significant seasonal variations in nitrite, nitrate, and ammonia concentrations in the Mayiladuthurai district, particularly in intake and discharge waters ($p < 0.05$), suggesting the influence of seasonal factors on water quality. In contrast, no significant seasonal differences were observed in the Nagapattinam district ($p > 0.05$), indicating relatively stable conditions across seasons. Taken together, the chemical, biological, and statistical evidence indicates that shrimp farming practices in the study area operate within permissible environmental limits. Nevertheless, the observed seasonal patterns underline the importance of continued water quality monitoring and adaptive management to support the long-term health of coastal aquatic ecosystems.

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Authors contributions. LCC was the lead author and made the primary contribution to this work. AS and ADAS contributed to conceptualization and methodology development. SS and DR provided supervision and technical guidance. MR and OP were responsible for field investigation, data collection, statistical analysis, and data validation. IP and SN contributed to resource management, visualization, manuscript editing, and documentation. SB assisted with the literature review and manuscript preparation.

Conflicts of interest. The authors declare that there is no conflict of interest.

Data availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Authors:

Lloyd Chrispin Christy (LCC), Department of Fisheries Extension, Economics and Statistics, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: lloyd@tnfu.ac.in

Aruna Satyapriyan (AS), Department of Aquatic Environment Management, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: aruna@tnfu.ac.in

Selvaraj Sethu (SS), Department of Aquaculture, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: selvaraj@tnfu.ac.in

Ilangamani Paramasivan (IP), Department of Fisheries Extension, Economics and Statistics, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: ilangamani05@gmail.com

Dinesh Rajan (DR), Department of Aquaculture, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: dinesh@tnfu.ac.in

Agnes Daney Angela Sam (ADAS), Department of Fisheries Extension, Economics and Statistics, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: angela@tnfu.ac.in

Manimaran Rasappan (MR), Department of Fisheries Extension, Economics and Statistics, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: manimaranr1833@gmail.com

Shweta Biswas (SB), Department of Fisheries Extension, Economics and Statistics, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: shwetabiswas11@gmail.com

Omprakash Shwian (OP), Department of Fisheries Extension, Economics and Statistics, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: omprakashfrz@gmail.com

Sarabes Nagendramani (SN), Department of Fisheries Extension, Economics and Statistics, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India, e-mail: sarabes461@gmail.com

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