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Environmental Assessment of Shrimp Hatcheries in Coastal Tamil Nadu of India

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Key words
Shrimp hatchery, Wastewater discharge, Water quality, Coastal aquaculture, Plankton diversity, Environmental impact

ABSTRACT

Shrimp hatcheries play a vital role in supporting coastal aquaculture by supplying quality seed for shrimp farming. However, wastewater discharge from hatchery operations may affect the surrounding aquatic environment by releasing nutrients and organic matter. The present study assessed the environmental implications of shrimp hatchery wastewater discharge in the Chengalpattu and Villupuram districts of Tamil Nadu, India. Six important water quality parameters, namely ammonia, nitrite, nitrate, chemical oxygen demand (COD), biological oxygen demand (BOD), and phosphate, were analyzed in intake water, discharge water, discharge-receiving water, and control site water during the pre-monsoon and monsoon seasons. Monthly samples were collected for 1 year from 10 purposively selected shrimp hatcheries, following APHA standard methods. Statistical analyses including One-Way ANOVA and Independent Samples *t*-tests were used to evaluate spatial and seasonal variations in water quality. Phytoplankton and zooplankton compositions were also examined to understand ecological responses associated with hatchery discharge. The results showed significantly higher nutrient and organic load concentrations in discharge water than in intake water and at control sites. However, all measured parameters remained within the permissible limits prescribed by the Coastal Aquaculture Authority (CAA), India. Phytoplankton analysis indicated moderate nutrient enrichment in hatchery-associated waters, while zooplankton diversity suggested minimal ecological disturbance. Overall, the study indicates that shrimp hatcheries presently operate within acceptable environmental standards. Nevertheless, continuous environmental monitoring and improved wastewater management practices are essential for ensuring the long-term sustainability of coastal aquaculture ecosystems.

INTRODUCTION

Shrimp aquaculture has emerged as one of the fastest-growing sectors in global food production due to the increasing demand for high-quality seafood and the economic opportunities it provides to coastal communities.

A key component supporting this industry is the shrimp hatchery, a specialized facility responsible for the controlled breeding, hatching, and rearing of shrimp larvae up to the post-larval (PL) stage before their transfer to grow-out farms. Hatcheries play a vital role in the aquaculture production chain by supplying healthy, genetically improved, and disease-free seed stocks to shrimp farms. Consequently, the sustainability and productivity of shrimp aquaculture largely depend on the efficient functioning of hatchery systems. India is among the world's leading shrimp-producing countries and has a well-established hatchery sector that significantly supports the aquaculture industry.

At present, more than 1,500 shrimp hatcheries are operating across the country, producing seed for both domestic use and commercial farming in major shrimp-

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producing regions. These hatcheries are an essential part of the aquaculture supply chain, ensuring the availability of high-quality, reliable seed stock, which is critical to maintaining farm productivity and biosecurity. In Tamil Nadu, shrimp farming is an important economic activity in several coastal districts. The industry witnessed rapid growth during the 1990s; however, it experienced a decline in the early 2000s due to disease outbreaks, excessive chemical use, and the devastating impacts of the 2004 Indian Ocean tsunami. The sector began to recover during the 2010s following the introduction and widespread adoption of the Pacific white shrimp, *Litopenaeus vannamei*, which offered improved growth performance and greater production reliability. According to the Coastal Aquaculture Authority (CAA, 2025), Tamil Nadu currently has 75 licensed shrimp hatcheries and 18 Nauplii Rearing Hatcheries (NRHs). A major concentration of these facilities is located in the districts of Villupuram and Chengalpattu. Villupuram district alone accounts for 38 hatcheries and 8 NRHs, while Chengalpattu district has 30 hatcheries and 9 NRHs. Together, these two districts represent nearly 91 per cent of the total shrimp hatcheries in the state. Despite their economic significance, shrimp hatcheries are highly water-intensive systems that generate substantial quantities of wastewater containing organic matter, nutrients, chemicals, and microbial loads. The accumulation of nitrogenous compounds during hatchery operations often leads to deterioration in water quality, necessitating frequent water exchange. However, the discharge of untreated hatchery wastewater poses serious environmental concerns. The disposal process can be costly and labour-intensive, and if improperly managed, may adversely affect the surrounding environment.

Many studies including Muralidhar and Gupta (2007) and Rabiei *et al*. (2014) have reported the nature of shrimp hatchery wastewater and its potential environmental impacts. But most of these studies have taken place in other geographical and operational environments and have concentrated on the quality of the wastewater and on general environmental issues. The environmental impact of hatchery clusters in Tamil Nadu is still largely unknown, especially in the districts of Chengalpattu and Villupuram that are home to most shrimp hatcheries in the State. Also, research that combines water quality assessment, plankton community response and local environmental condition with specific reference to hatchery wastewater outflow is limited. Besides, these two districts contain 68 of the 75 licensed shrimp hatcheries approximately 91 percent in Tamil Nadu and district level assessment is essential to understand the cumulative environmental impacts of hatchery operations and to provide scientific evidence for sustainable management and regulatory compliance.

Wastewater released from hatcheries can contribute to nutrient enrichment and eutrophication in nearby rivers, estuaries, and coastal waters, thereby affecting aquatic ecosystems and the livelihoods of local communities. In addition, shrimp hatcheries have faced social opposition and legal scrutiny due to concerns regarding environmental pollution and the potential impacts on groundwater quality, soil characteristics, agricultural activities, and public health. Allegations regarding hatchery wastewater discharge have led to several petitions and legal cases filed by local farmers and other stakeholders before regulatory bodies, including the National Green Tribunal and the High Court. These concerns highlight the need for systematic evaluation of the environmental impacts associated with shrimp hatchery operations. In this context, the present study was undertaken to document and assess the environmental impacts of selected shrimp hatcheries located in the Chengalpattu and Villupuram districts of Tamil Nadu.

MATERIALS AND METHODS

Study sites and sampling plan

The present study was carried out in the coastal districts of Chengalpattu and Villupuram in Tamil Nadu, India, selected for their high concentration of shrimp hatcheries. A total of ten shrimp hatcheries were purposively selected to ensure adequate geographical representation within each district. For systematic sampling, two clusters were identified in each district, resulting in a total of four clusters. Five shrimp hatcheries were selected from each district for detailed investigation. The selected shrimp hatcheries had wastewater management facilities such as sedimentation tanks, filtration systems, biofilters, and chlorination/dechlorination units. The facilities are used to lower suspended solids, organic matter and nutrient levels prior to wastewater discharge to the environment. Information on these facilities was recorded during field visits and considered while interpreting the water quality results.

Thiruvidanthai village in Chengalpattu district and Koonimedu village in Villupuram district were selected as control sites because these locations did not contain shrimp hatcheries and thus served as reference environments for comparison. The control sites were selected to represent coastal ecosystems with hydrological and ecological characteristics that are generally similar to those of the hatchery-associated sites in terms of salinity regime, tidal influence and coastal environmental conditions. Furthermore, the chosen control sites were not receiving direct shrimp hatchery wastewater and were not experiencing significant changes from aquaculture activity, making them an appropriate indicator of the environmental changes associated with the hatchery. Water samples were collected during two major seasonal periods, namely the pre-monsoon and monsoon seasons. The sampling included intake water, discharge water, discharge-receiving water, and water from control sites. In addition, plankton samples were collected simultaneously from the same locations for biological analysis. Monthly sampling was conducted at the selected shrimp hatcheries in both districts throughout the study period. All analyses were performed following the procedures outlined in the standard methods for the examination of water and wastewater (APHA, 2017).

A total of 10 shrimp hatcheries were randomly selected from four clusters in Chengalpattu and Villupuram, and monitored during the period of April to December 2022. Two hatcheries were sampled in Cluster I of Chengalpattu with the collection of 54 water samples. Chengalpattu Cluster II had three hatcheries and 81 water samples were collected from them. Likewise, the cluster I of Villupuram had three hatcheries and a total of 81 water samples were collected, and the cluster II of Villupuram had two hatcheries and 54 water samples were collected. Water samples were taken from intake water, discharge water and discharge-receiving water for every hatchery. Two control sites were sampled at the same time, which gave 18 control water samples. During the entire study, a total of 288 water samples were collected.

The environmental assessment focused on six important water quality parameters: ammonia, nitrite, nitrate, chemical oxygen demand (COD), biological oxygen demand (BOD), and phosphate. These non-conservative water quality parameters were selected because elevated concentrations can adversely affect aquatic organisms and the surrounding environment (John *et al*., 2020). Therefore, monitoring these parameters is essential for evaluating the environmental sustainability and ecological safety of shrimp hatchery operations. Phytoplankton and zooplankton samples collected from the study sites were analyzed to determine species composition and abundance.

Plankton sampling and analysis

Plankton samples were collected simultaneously with water sampling at all study locations. For phytoplankton analysis, 50 L volume of water was filtered through a plankton net of 20 µm mesh size, while zooplankton samples were collected by filtering 100 L of water through a 60 µm mesh size plankton net. The concentrated samples were preserved immediately in 4% buffered formalin solution and transported to the laboratory for analysis. Identification of phytoplankton and zooplankton taxa was carried out using standard taxonomic keys and identification manuals. Enumeration was performed using a Sedgwick–Rafter counting cell under a compound microscope. Organisms were identified up to the genus level wherever possible, and abundance was expressed as percentage composition of the total plankton community observed in each sample.

Prior to statistical analysis, Levene's test was performed to assess homogeneity of variances among groups, and the assumptions required for parametric analyses were evaluated. To evaluate spatial variations in water quality, One-Way Analysis of Variance (ANOVA) was conducted to identify statistically significant differences among intake water, discharge water, discharge-receiving water, and control site water for the six selected parameters. In addition, Independent Samples *t*-tests were employed to determine seasonal variations in parameter concentrations between the pre-monsoon and monsoon periods in both districts. All statistical analyses were performed at a significance level of $p < 0.05$.

Furthermore, One-Way ANOVA followed by post hoc analysis using Duncan's Multiple Range Test (DMRT) was employed to determine differences among sampling sites. Differences between mean values were considered statistically significant at $p < 0.05$, whereas values showing no significant variation were treated as statistically similar. Superscript letters were assigned according to the relative magnitude of parameter concentrations, with the letter "a" representing the lowest mean concentration and subsequent letters indicating progressively higher mean values. These superscript annotations were incorporated into all graphical representations of the physicochemical parameters.

RESULTS AND DISCUSSION

Spatial comparison of water quality parameters

The study assessed six water quality parameters: ammonia, nitrite, nitrate, COD, BOD and phosphate across four distinct sample types: intake water, discharge water, discharge-receiving water and control site during the pre-monsoon and monsoon seasons. The average parameter values for each category were calculated from clusters I and II of both Chengalpattu and Villupuram districts. The average values from both districts were combined to give an overall range for each category. These results were compared with the permissible limits prescribed by the Coastal Aquaculture Authority (CAA), which are presented in Table I alongside the observed values to facilitate direct assessment of compliance.

Table I. Permissible limits for key water quality parameters in shrimp hatchery final discharge water (mg L^{-1}) (Source: CAA, 2026).

Parameter	Intake water (mg L^{-1})	Discharge water (mg L^{-1})	Discharge-receiving water (mg L^{-1})	Control site (mg L^{-1})	CAA permissible limit (mg L^{-1})
Ammonia	0.050–0.129	0.368–0.446	0.015–0.020	0.003–0.006	0.50
Nitrite	0.016–0.070	0.143–0.232	0.038–0.078	0.004–0.029	Not Specified
Nitrate	0.110–0.274	0.270–0.542	0.269–0.463	0.135–0.268	Total Nitrogen ≤ 2.0*
Phosphate	0.043–0.065	0.114–0.193	0.066–0.160	0.086–0.160	0.20
COD	4.70–6.26	8.20–11.00	8.42–11.01	5.50–6.90	75
BOD	1.60–2.28	3.67–4.54	3.76–4.53	2.52–3.75	20

Note: CAA permissible limits are based on the Coastal Aquaculture Authority (CAA, 2026) standards for wastewater discharged from aquaculture hatcheries and related facilities.

Ammonia

During the pre-monsoon season, ammonia concentrations in the studied water samples ranged from 0.015 to 0.388 mg L^{-1}. The intake water recorded ammonia levels between 0.050 and 0.053 mg L^{-1}, while discharge water showed comparatively higher concentrations ranging from 0.368 to 0.388 mg L^{-1}. Discharge-receiving water exhibited lower concentrations between 0.015 and 0.016 mg L^{-1}, whereas the control sites recorded the lowest ammonia levels ranging from 0.003 to 0.005 mg L^{-1}. During the monsoon season, ammonia concentrations increased slightly across all sampling categories. Intake water recorded values between 0.124 and 0.129 mg L^{-1}, discharge water ranged from 0.438 to 0.446 mg L^{-1}, and discharge-receiving water showed concentrations between 0.016 and 0.020 mg L^{-1}. Similar to the pre-monsoon season, the control sites exhibited comparatively lower ammonia levels ranging from 0.004 to 0.006 mg L^{-1}. Although ammonia concentrations in the discharge water were elevated relative to the ambient water samples, all observed values remained within the permissible limits prescribed by the CAA during both seasons.

One-Way ANOVA was performed to compare ammonia concentrations among the four water categories, namely intake water, discharge water, discharge-receiving water, and control site water. The analysis revealed a highly significant difference in ammonia concentrations among the sampling categories ($F = 173.756$, $p = 0.000$). Post hoc comparison using DMRT indicated that ammonia concentrations were lowest in the control site water and highest in the discharge water, while intake water and discharge-receiving water exhibited intermediate values. The ammonia concentrations observed in the discharge water during the present study were considerably higher than the values reported by Muralidhar and Gupta (2007) for the Muttukadu hatchery (0.057 mg L^{-1}) and Suryalanka hatchery (0.009 mg L^{-1}). However, the observed values were lower than those reported by Rabiei *et al*. (2014), who recorded ammonia concentrations of 1.00 ± 0.01 mg L^{-1} in *Penaeus monodon* hatchery discharge water. Similarly, ammonia concentrations in the discharge-receiving water of the present study were lower than those reported for the Muttukadu hatchery (0.050 mg L^{-1}) but higher than the values reported for the Suryalanka hatchery (0.012 mg L^{-1}) by Muralidhar and Gupta (2007).

Nitrite

During the pre-monsoon season, nitrite concentrations in the studied water samples ranged from 0.004 to 0.217 mg L^{-1}. Intake water recorded nitrite concentrations between 0.020 and 0.070 mg L^{-1}, while discharge water exhibited comparatively higher concentrations ranging from 0.143 to 0.217 mg L^{-1}. Discharge-receiving water showed intermediate concentrations between 0.044 and 0.069 mg L^{-1}, whereas the control site recorded the lowest nitrite levels ranging from 0.004 to 0.013 mg L^{-1}. The gradual increase in nitrite concentration from intake water to discharge water, with intermediate values observed in discharge-receiving water, reflects the characteristic discharge pattern associated with regular shrimp hatchery operations. During the monsoon season, a similar trend in nitrite concentrations was observed across the sampling categories. Intake water recorded nitrite levels between 0.016 and 0.043 mg L^{-1}, discharge water ranged from 0.154 to 0.232 mg L^{-1}, and discharge-receiving water showed concentrations between 0.038 and 0.078 mg L^{-1}. In contrast, the control site continued to exhibit comparatively lower nitrite concentrations ranging from 0.006 to 0.029 mg L^{-1}. The observed nitrite concentrations were consistently higher in hatchery-associated water samples than in the control site water. However, all recorded values remained within the permissible discharge limits prescribed by the CAA during both seasons, indicating compliance with environmental standards.

One-Way ANOVA revealed significant differences in nitrite concentrations among the four water categories ($F= 11.733$, $p= 0.001$). Post hoc comparison using DMRT indicated that discharge water had significantly higher nitrite concentrations than intake water, discharge-receiving water, and control site water. These findings suggest localized environmental loading associated with hatchery discharge activities. The nitrite concentrations observed in the discharge water during the present study were substantially higher than those reported by Muralidhar and Gupta (2007) for the Muttukadu hatchery (0.03 mg L^{-1}) and Suryalanka hatchery (0.02 mg L^{-1}). Similarly, the observed nitrite levels were higher than those reported by Rabiei *et al*. (2014), who documented nitrite concentrations of 0.13 ± 0.01 mg L^{-1} in *Penaeus monodon* hatchery discharge water. Furthermore, nitrite concentrations in the discharge-receiving water of the present study were higher than those reported for the Muttukadu hatchery (0.009 mg L^{-1}) and Suryalanka hatchery (0.021 mg L^{-1}) by Muralidhar and Gupta (2007).

Nitrate

During the pre-monsoon season, nitrate concentrations in the studied water samples ranged from 0.110 to 0.377 mg L^{-1}. Intake water recorded nitrate concentrations between 0.110 and 0.172 mg L^{-1}, while discharge water showed comparatively higher concentrations ranging from 0.270 to 0.278 mg L^{-1}. Discharge-receiving water exhibited concentrations between 0.269 and 0.377 mg L^{-1}, whereas the control site recorded comparatively lower concentrations ranging from 0.135 to 0.141 mg L^{-1}. The elevated nitrate concentrations observed in discharge water and discharge-receiving water indicate moderate nutrient enrichment along the hatchery discharge pathway. During the monsoon season, nitrate concentrations increased across most sampling categories. Intake water recorded concentrations between 0.156 and 0.274 mg L^{-1}, discharge water ranged from 0.480 to 0.542 mg L^{-1}, and discharge-receiving water exhibited concentrations between 0.453 and 0.463 mg L^{-1}. In contrast, nitrate concentrations at the control site ranged from 0.242 to 0.268 mg L^{-1}, which were marginally higher than some intake water samples. Despite these seasonal variations, all recorded nitrate concentrations remained well within the permissible discharge limits prescribed by the CAA, indicating compliance with environmental quality standards during both seasons.

One-Way ANOVA revealed significant differences in nitrate concentrations among the four water categories ($F= 6.055$, $p= 0.009$). Post hoc comparison using DMRT grouped discharge water and discharge-receiving water within the higher concentration subset, while intake water and control site water formed the lower subset. These findings indicate nutrient accumulation associated with hatchery operations and wastewater discharge. The nitrate concentrations observed in the discharge water during the present study were substantially higher than those reported by Muralidhar and Gupta (2007) for the Muttukadu hatchery (0.02 mg L^{-1}) and Suryalanka hatchery (0.21 mg L^{-1}). Compared with the findings of Rabiei *et al*. (2014), who reported nitrate concentrations of 0.40 ± 0.01 mg L^{-1} in *Penaeus monodon* hatchery discharge water, the present study recorded lower nitrate concentrations during the pre-monsoon season but comparatively higher concentrations during the monsoon season. Furthermore, nitrate concentrations in the discharge-receiving water of the present study were considerably higher than those reported for the Muttukadu hatchery (0.018 mg L^{-1}) and Suryalanka hatchery (0.16 mg L^{-1}) by Muralidhar and Gupta (2007).

Phosphate

Phosphate concentrations recorded during the present study indicated noticeable nutrient enrichment in hatchery discharge water and adjacent receiving environments. During the pre-monsoon season, intake water exhibited comparatively lower phosphate concentrations ranging from 0.043 to 0.061 mg L^{-1}. In contrast, elevated phosphate levels were observed in discharge water (0.114 to 0.193 mg L^{-1}) and discharge-receiving water (0.109 to 0.150 mg L^{-1}) when compared to the control site, which recorded concentrations between 0.086 and 0.111 mg L^{-1}. These findings suggest phosphate enrichment associated with shrimp hatchery operational activities and wastewater discharge. A similar trend was observed during the monsoon season. Intake water recorded phosphate concentrations between 0.051 and 0.065 mg L^{-1}, whereas discharge water showed higher concentrations ranging from 0.150 to 0.177 mg L^{-1}. Discharge-receiving water exhibited a comparatively broader concentration range between 0.066 and 0.160 mg L^{-1}. The control site also recorded relatively higher phosphate concentrations during this season, ranging from 0.130 to 0.160 mg L^{-1}. Despite seasonal fluctuations, phosphate concentrations remained consistently elevated in discharge and discharge-receiving water during both seasons. Nevertheless, all observed values were within the permissible discharge limits prescribed by the CAA.

One-Way ANOVA revealed significant differences in phosphate concentrations among the four water categories ($F= 6.683$, $p= 0.007$). DMRT further demonstrated that intake water possessed the lowest phosphate concentrations, whereas discharge water recorded the highest values. Discharge-receiving water showed concentrations comparable to the control site water, indicating gradual phosphate accumulation along the discharge flow pathway.

The phosphate concentrations observed in the discharge water during the present investigation were considerably higher than those reported by Muralidhar and Gupta (2007) for the Muttukadu hatchery (0.019 mg L^{-1}) and Suryalanka hatchery (0.009 mg L^{-1}). However, the phosphate levels recorded in the present study were lower than those documented by Rabiei *et al.* (2014), who reported phosphate concentrations of 0.40 ± 0.01 mg L^{-1} in *Penaeus monodon* hatchery discharge water. Similarly, phosphate concentrations in discharge-receiving water were higher than those reported for the Muttukadu hatchery (0.014 mg L^{-1}) and Suryalanka hatchery (0.008 mg L^{-1}) by Muralidhar and Gupta (2007).

COD

The COD concentrations observed in the present study clearly reflected the influence of shrimp hatchery discharge on the surrounding aquatic environment. During the pre-monsoon season, comparatively lower COD values were recorded in intake water, ranging from 4.70 to 5.34 mg L^{-1}. In contrast, discharge water exhibited elevated COD concentrations between 8.20 and 9.38 mg L^{-1}, while discharge-receiving water showed values ranging from 8.42 to 9.37 mg L^{-1}. The control sites recorded comparatively moderate concentrations between 5.5 and 6.9 mg L^{-1}. A similar trend was observed during the monsoon season. Intake water contained COD concentrations ranging from 5.74 to 6.26 mg L^{-1}, whereas substantially higher values were observed in discharge water (10.9 to 11.0 mg L^{-1}) and discharge-receiving water (9.37 to 11.01 mg L^{-1}). Control site water recorded relatively lower COD concentrations ranging from 5.5 to 6.7 mg L^{-1}. The increased COD levels in discharge and discharge-receiving water indicate the addition of organic matter from hatchery operations, which may contribute to increased oxygen demand in adjacent aquatic systems. Nevertheless, all recorded COD values remained within the permissible limits prescribed by the CAA during both seasonal periods.

Statistical analysis using One-Way ANOVA demonstrated highly significant variation in COD concentrations among the four sampling categories ($F= 20.434$, $p= 0.000$). DMRT further confirmed that discharge water and discharge-receiving water formed the higher concentration group, while intake water and control site water were grouped under comparatively lower concentrations. These findings suggest that hatchery effluents significantly influence the organic load of receiving waters in the vicinity of the hatcheries. The COD concentrations recorded in the present investigation were higher than those reported by Muralidhar and Gupta (2007) for the Muttukadu hatchery (1.2 mg L^{-1}) and were comparable to values observed in the Suryalanka hatchery (10 mg L^{-1}). However, the present COD levels were substantially lower than those reported by Rabiei *et al.* (2014), who documented COD concentrations of 320 ± 28 mg L^{-1} in *Penaeus monodon* hatchery discharge water. Similarly, COD concentrations in discharge-receiving water were greater than the values reported for the Muttukadu hatchery (1.8 mg L^{-1}) and closely comparable with those observed in the Suryalanka hatchery (10.3 mg L^{-1}) by Muralidhar and Gupta (2007).

BOD

The BOD levels recorded during the present investigation indicated increased organic enrichment in shrimp hatchery discharge waters and nearby receiving environments. During the pre-monsoon season, intake water exhibited comparatively lower BOD concentrations ranging from 1.60 to 1.76 mg L^{-1}. In contrast, higher concentrations were observed in discharge water (3.67 to 3.82 mg L^{-1}) and discharge-receiving water (3.76 to 4.03 mg L^{-1}). The control site recorded intermediate values ranging from 2.52 to 3.23 mg L^{-1}. A similar pattern was observed during the monsoon season. Intake water contained relatively lower BOD concentrations ranging from 2.05 to 2.28 mg L^{-1}, whereas discharge water showed elevated values between 4.45 and 4.54 mg L^{-1}. Discharge-receiving water also exhibited comparatively higher BOD concentrations ranging from 4.05 to 4.53 mg L^{-1}, while the control site recorded values between 3.05 and 3.75 mg L^{-1}. These observations indicate a consistent increase in organic matter load in hatchery discharge water and adjacent receiving waters. However, all measured BOD concentrations remained within the permissible discharge limits prescribed by the CAA, suggesting compliance with prevailing environmental regulations.

Statistical analysis using One-Way ANOVA revealed significant variation in BOD concentrations among the four water categories ($F= 26.635$, $p= 0.000$). DMRT further indicated that discharge water and discharge-receiving water formed the higher concentration groups compared to intake water. The control site water formed a distinct intermediate group, reflecting the influence of hatchery-derived organic matter enrichment along the discharge pathway and its subsequent impact on surrounding aquatic environments. The discharge water BOD concentrations observed in the present study were substantially higher than those reported by Muralidhar and Gupta (2007) for the Muttukadu hatchery (0.5 mg L^{-1}), but lower than the concentrations reported for the Suryalanka hatchery (9 mg L^{-1}). Similarly, BOD concentrations in discharge-receiving water were considerably higher than those observed for the Muttukadu hatchery (0.85 mg L^{-1}), but lower than those recorded for the Suryalanka hatchery (5.2 mg L^{-1}) by Muralidhar and Gupta (2007).

Seasonal comparison of water quality parameters

To evaluate temporal variations in water quality, independent samples *t*-tests were performed to compare the seasonal differences between the pre-monsoon and monsoon periods for six selected water quality parameters in intake water, discharge water, and discharge-receiving water from the Chengalpattu and Villupuram districts. In the intake water samples from Chengalpattu district, significant seasonal variation was observed only for nitrite concentration (p = 0.03), while the remaining parameters did not exhibit statistically significant differences between seasons. BOD showed borderline significance (p = 0.050), with a mean decrease of 0.524 mg L^{-1} during the monsoon period. However, when unequal variances were assumed, the adjusted p-value increased to 0.066, indicating a statistically non-significant difference. The near-significant variation in BOD suggests a possible seasonal influence on organic matter content in the intake water. Overall, these findings indicate relatively stable intake water quality across seasons, except for nitrite, which may require closer monitoring during monsoon-related hatchery activities.

In Villupuram district, intake water exhibited statistically significant seasonal variation only in COD concentrations (p= 0.04), indicating notable changes in organic load between seasons. The remaining parameters did not show significant seasonal differences, suggesting comparatively stable physicochemical conditions in the intake water throughout the study period. Seasonal comparison of discharge water samples from Chengalpattu district revealed statistically significant variations in COD (p= 0.027), nitrate (p= 0.043), and BOD (p= 0.016). These results indicate that organic load and nutrient concentrations in hatchery discharge water are influenced by seasonal and monsoonal changes. In contrast, ammonia, nitrite, and phosphate concentrations did not differ significantly between seasons ($p > 0.05$), suggesting relatively consistent discharge characteristics throughout the year. In Villupuram district, discharge water samples exhibited significant seasonal differences in ammonia (p= 0.003), nitrite (p= 0.000), nitrate (p= 0.032), and phosphate (p= 0.013), indicating marked seasonal fluctuations in nutrient concentrations. However, COD and BOD did not show statistically significant seasonal variation ($p >$ 0.05), suggesting that the organic load in discharge water remained relatively stable across seasons.

For discharge receiving water samples in Chengalpattu district, statistically significant seasonal variation was observed only for BOD (p= 0.011). The comparatively lower BOD concentrations during the monsoon season may be attributed to dilution effects caused by increased freshwater inflow and rainfall. The remaining parameters did not show significant seasonal differences ($p > 0.05$), indicating stable water quality conditions in the receiving environment across seasons. In contrast, none of the assessed parameters in discharge-receiving water from Villupuram district, including ammonia, nitrite, nitrate, COD, BOD, and phosphate, exhibited statistically significant seasonal variation (p > 0.05). These results indicate that the physicochemical characteristics of receiving waters in Villupuram district remained relatively consistent between the pre-monsoon and monsoon seasons.

Phytoplankton composition

The comparative analysis of phytoplankton composition between the control and hatchery sites in Chengalpattu and Villupuram districts revealed notable variations in community structure, reflecting differences in nutrient availability and environmental conditions associated with shrimp hatchery activities. In Chengalpattu district, the control site was predominantly composed of diatoms (46.50%), followed by green algae (30.23%) and dinoflagellates (23.25%), whereas blue-green algae were absent. The dominance of diatoms and green algae indicates relatively stable and less nutrient-enriched environmental conditions. In contrast, the hatchery site exhibited a clear shift in phytoplankton composition, with diatoms accounting for 38.47% and dinoflagellates emerging as a dominant group (34.61%). Blue-green algae constituted 26.92% of the total phytoplankton population, while green algae were entirely absent. The increased abundance of dinoflagellates and blue-green algae at the hatchery site suggests nutrient enrichment and altered ecological conditions associated with hatchery discharge.

A similar trend was observed in Villupuram district. At the control site, green algae formed the dominant group (38.70%), followed by diatoms (25.80%) and dinoflagellates (19.38%), while blue-green algae were absent. However, at the hatchery site, diatoms dominated the phytoplankton community (34.48%), followed by dinoflagellates (27.58%), blue-green algae (24.13%), and green algae (13.79%). The comparatively higher proportion of blue-green algae and dinoflagellates at the hatchery sites indicates nutrient enrichment resulting from hatchery operations. Diatoms and green algae are generally considered indicators of good water quality and ecologically stable aquatic environments with lower nutrient enrichment (Datta *et al.*, 2019). Conversely, increased nutrient loading in aquatic systems often promotes the proliferation of dinoflagellates and blue-green algae, particularly under eutrophic conditions

(Anderson *et al*., 2012). The phytoplankton composition observed in the present study therefore suggests that hatchery discharge influences nutrient dynamics and alters the ecological characteristics of adjacent aquatic ecosystems.

Zooplankton composition

The zooplankton composition at hatchery and control sites in Chengalpattu and Villupuram districts exhibited distinct differences in diversity and dominance patterns, indicating the ecological influence of hatchery activities on aquatic communities. In Chengalpattu district, the control site supported a comparatively diverse zooplankton assemblage comprising tintinnids (32.29%), copepods (16.12%), mysis larvae, amphipods, rotifers, ostracods, and fish eggs. The dominance of tintinnids at the control site suggests relatively low nutrient enrichment and stable environmental conditions. Similar findings were reported by Zhang *et al*. (2017), who observed a strong association between tintinnid abundance and lower nutrient conditions. In contrast, the hatchery site in Chengalpattu district was strongly dominated by copepods (46.15%) and their larval forms, including nauplii (30.76%) and *Calanus* species (23.07%), while other zooplankton groups were absent. The reduction in overall zooplankton diversity and increased dominance of copepods may be attributed to elevated organic loading and nutrient enrichment associated with hatchery discharge. Luan *et al*. (2024) similarly reported that increased organic matter enrichment promotes copepod dominance while reducing overall zooplankton diversity in aquatic ecosystems.

In the Villupuram district, copepods constituted the dominant zooplankton group at both the control and hatchery sites. At the control site, copepods accounted for 32.14% of the zooplankton population, followed by nauplii (17.85%) and *Calanus* species (14.28%). A comparable pattern was observed at the hatchery site, where copepods formed the dominant group (43.75%), followed by nauplii (31.25%) and *Calanus* species (25%). The higher proportion of copepods and larval stages at hatchery sites indicates favourable nutrient-rich conditions that support rapid zooplankton proliferation. The zooplankton composition observed in the present study demonstrates that hatchery discharge influences aquatic food web structure and community dynamics by promoting nutrient-tolerant zooplankton groups while reducing overall biodiversity. The observed changes in the phytoplankton and zooplankton community were closely correlated with the changes in the water quality characteristics of the hatchery discharge waters. Higher nitrate, phosphate, ammonia, COD and BOD levels in discharge and discharge receiving waters are signs of an increase in nutrient and organic matter load in the hatchery discharges. The over-enrichment created by these circumstances may have favoured the growth of phytoplankton groups that are tolerant to nutrients, for example, dinoflagellates and blue-green algae, which were more plentiful at the hatchery sites than at control sites. Likewise, the higher concentrations of COD and BOD, indicating higher concentrations of organic matter, might have supported increased microbial productivity and food levels which would have favoured the dominance of copepods and their larval stages in the zooplankton community. Despite the biological changes, which imply moderate ecological response to nutrient enrichment, the continued presence of various groups of plankton, and the absence of excessive algal blooms, suggest that the receiving waters had still enough assimilative capacity to limit ecological disturbance. The results have shown that water quality parameters and plankton community structure are interdependent and that both factors are good indicators of the impact of shrimp wastewater discharge on the environment.

CONCLUSION

The present study assessed the environmental impacts of shrimp hatchery wastewater discharge in the Chengalpattu and Villupuram districts of Tamil Nadu by analysing key water quality parameters and plankton composition. The concentrations of ammonia, nitrite, nitrate, COD, BOD, and phosphate in intake water, discharge water, and discharge-receiving water were found to be within the permissible limits prescribed by the CAA. These findings indicate that the hatchery discharges presently pose limited risk of severe nutrient enrichment, organic pollution, or oxygen depletion in the surrounding aquatic environment.

Seasonal variations were observed in certain water quality parameters, particularly nitrite, COD, nitrate, and BOD in Chengalpattu district, and ammonia, nitrite, nitrate, and phosphate in the discharge water of Villupuram district. However, the discharge-receiving waters generally exhibited stable conditions, suggesting the buffering and dilution capacity of the receiving coastal environment. Phytoplankton analysis revealed the dominance of diatoms and green algae at control sites, indicating comparatively stable ecological conditions, whereas hatchery sites showed increased abundance of dinoflagellates and blue-green algae, reflecting moderate nutrient enrichment. Zooplankton analysis demonstrated the dominance of copepods and their larval stages at both control and hatchery sites, suggesting that hatchery discharge had no major adverse effect on the surrounding coastal fishery environment and biological productivity. The results of the zooplankton analysis showed that copepods and their larval stages predominated at both control and hatchery sites. The nutrient and organic load concentration in the waters receiving the discharges exceeded the thresholds that are allowed by the Coastal Aquaculture Authority (CAA). however, the levels of these parameters are moderate and there is a visible shift in the plankton species composition. Based on these findings, it seems that existing hatchery operations are not leading to major environmental deterioration, but continued monitoring and assessment with ecological indicators and long-term datasets will be required to thoroughly assess potential environmental impacts.

Overall, the results suggest that the existing shrimp hatcheries in the study area are operating within acceptable environmental standards, aided by the natural dilution capacity of the coastal ecosystem. Nevertheless, continuous environmental monitoring, periodic assessment, and adoption of improved wastewater management strategies are essential to ensure the long-term sustainability of shrimp hatchery operations. Future studies should focus on long-term ecological monitoring, carrying capacity assessment, advanced wastewater treatment technologies, and ecosystem-based management approaches for sustainable coastal aquaculture development.

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The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

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