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Monitoring of Water Quality and Pollution Index in Intensive Pacific White Shrimp *(Litopenaeus vannamei)* Cultivation in Buleleng Regency, Bali Province, Indonesia

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ABSTRACT

Litopenaeus vannamei is one of the main commodities of the aquaculture sector in Indonesia. To support export needs to several countries, intensification activities in *L. vannamei* cultivation have been carried out in several regions in Indonesia including the North Coast of Bali Province. This intensification activity is one of the causes of the decline in the quality of the coastal environment due to the high supply of organic waste materials that are related to the coastal environment without prior processing. This study aimed to asses the quality of wastewater from *L. vannamei* cultivation that had been carried out in Gerokgak District, Buleleng Regency, Bali Province. The results of this study showed that temperature, turbidity, DO, BOD, COD, nitrate, nitrite, ammonia, and organic substances in wastewater had significant differences between sampling locations. The highest water pollution index analysis occurred at station 3 in Patas Village with a "heavy pollution" index value. The pH, temperature, and COD values were among the factors affecting the quality of *L. vannamei* pond wastewater in general based on PCA analysis. The findings of this study confirmed that wastewater from *L. vannamei* cultivation using an intensive system may reduce water quality in coastal areas, therefore it is highly recommended to install a wastewater treatment plant to support a sustainable aquaculture system.

INTRODUCTION

The consumption level of fishery products is estimated to reach one million tons globally by 2023 **(Rajeev *et al.* ,2021)**. This has attracted attention to the seafood industry, especially in the global trade sector. To meet consumer demand, aquaculture has become one of the most promising industries in food production and currently contributes nearly half of the world's total fishery output **(Zakaria *et al.*, 2022; Samara *et al.*, 2024; Rahim *et al.*, 2025)**. Crustacean products alone contribute more than 150 billion USD in international fisheries trade **(Patil *et al.*, 2021)**. Crustaceans, including the Pacific white shrimp (*Litopenaeus vannamei*), tiger prawns (*Penaeus monodon*), mud crabs (*Scylla* sp.), and mitten crabs are among the most widely cultivated species globally, including in Indonesia **(Seong Wei *et al.*, 2024; Amin *et al.*, 2025; Arifin *et al.*, 2025; Satyantini *et al.*, 2025)**.

In the past 20 years, world shrimp production has increased by nearly 3 million tons annually. In Indonesia, the rapid rise in *L. vannamei* production was first recorded in 2004, surpassing *P. monodon* in 2007. By 2020, *L. vannamei* production was 2.5 times higher than *P. monodon*, which stood at 722 thousand tons **(Asmild *et al.*, 2024)**. Gerokgak District, Buleleng Regency, is one of the regions within Buleleng that serves as a central location for marine and brackish water aquaculture activities in Bali. Various types of aquaculture, including *L. vannamei* cultivation, have been developed in Gerokgak District. According to data from the **Food Security and Fisheries Service of Buleleng Regency (2022)**, Buleleng has aquaculture potential covering 4,921 ha, though only 415.30 ha have been utilized, yielding 3,542.09 tons of production. This includes seawater commodities (495.61 tons), brackish water commodities (3,000 tons), and freshwater commodities (46.48 tons). Based on these figures, aquaculture in brackish water—particularly *L. vannamei*—and seawater commodities like grouper dominate over freshwater aquaculture.

Production increases are made possible through intensive farming systems, which involve higher stocking densities and the use of high-protein feed **(Wiradana *et al.*, 2023)**. Shrimp feed typically contains 30–40% crude protein, of which only 20–25% is absorbed by shrimp; the remainder becomes organic waste at the pond bottom. Research indicates that every kilogram of shrimp feed consumed can result in up to 50 g of ammonia nitrogen. Additionally, shrimp feces and dead organisms contribute ammonia (NH_3), nitrite (NO_2), and hydrogen sulfide (H_2S) to the pond water, rendering it unsuitable for reuse **(Iber *et al.*, 2021)**. In intensive systems, up to 30% of pond water may be discharged weekly, releasing 35–72% of the nitrogen content into surrounding environments.

Despite the industry's economic significance, little information exists on the environmental impact of shrimp farming waste **(Sanguanrut *et al.*, 2018; Odeyemi *et al.*, 2021; Rahardjo *et al.*, 2023)**. Water pollution, biodiversity loss, and habitat degradation resulting from waste accumulation and discharge are pressing issues in modern aquaculture systems **(Ni *et al.*, 2021)**. These issues not only reduce yields but also harm surrounding ecosystems, potentially causing conflict between shrimp farmers and other stakeholders. Furthermore, several diseases commonly affect intensively farmed shrimp, significantly impacting productivity **(Patil *et al.*, 2021)**. Such diseases include gill-associated virus (GAV) **(Cowley *et al.*, 2000)**, yellow head virus (YHV) **(Mohr *et al.*, 2015)**, vibriosis, white spot syndrome virus (WSSV) **(Domínguez-Borbor *et al.*, 2019; Wiradana *et al.*, 2019)**, infectious hypodermal and hematopoietic necrosis virus (IHHNV) **(Sellars *et al.*, 2019)**, early mortality syndrome (EMS) or acute hepatopancreatic necrosis disease (AHPND) **(Deris *et al.*, 2020)**, and microsporidiosis caused by *Enterocytozoon hepatopenaei* **(Mithun Raj *et al.*, 2023)**.

Monitoring aquaculture wastewater is essential for ensuring compliance with environmental regulations and mitigating water-related hazards. Sampling locations and monitoring frequency should be based on the spatial and temporal dynamics of *L. vannamei* farming. Numerous studies have investigated the relationship between water quality and pollution indices in aquaculture. For instance, integrating mangrove systems into shrimp farming has revealed significant differences in water parameters—such as temperature, dissolved oxygen, and nitrite—across observation sites. Principal Component Analysis (PCA) identified total organic matter (TOM), nitrate, nitrite, and ammonia as key indicators of water quality in intensive *L. vannamei* systems, with results indicating a moderate pollution index **(Mahmudi *et al.*, 2022)**. Based on this background, the objective of this study is to evaluate the temporal wastewater quality and pollution index of *L. vannamei* cultivation in Gerokgak District, Buleleng Regency, Bali, Indonesia. This research aimed to provide baseline data on environmental pollution levels from shrimp aquaculture and to support the need for technological improvements in wastewater management **(Li*et al.*, 2019; Ni*et al.*, 2021)**.

MATERIALS AND METHODS

Area of study

The study employed a descriptive method with a quantitative approach. Water and sediment waste samples were collected from three Pacific white shrimp (*L. vannamei*) culture outlets. Sampling was carried out at intensive shrimp farming sites located in Patas Village, Gerokgak Village, and Sanggalangit Village, Buleleng Regency, Bali Province (Fig. 1). Detailed coordinates of the study sites are provided in Table (1). Each location included three sampling points for both water and sediment waste collection. All samples were analyzed at the UPTD Kerthi Bali Sadhajiwa Health Laboratory Center, Bali Province, and the Joint Analyst Laboratory of Udayana University (UNUD).

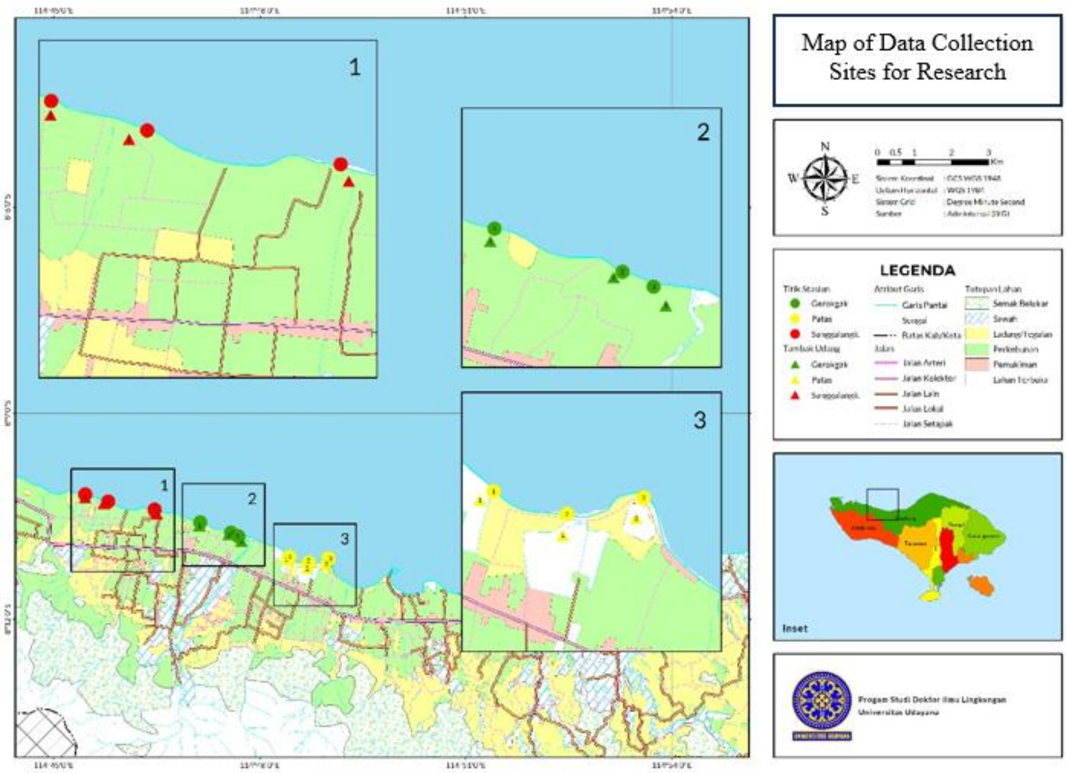

Fig. 1. Sampling locations at each station in this study

Table 1. Coordinates of the study sites

Site	Coordinate
Patas Village	8°11′21″S 114°48′01″E / 8.189261°S 114.800189°E
Gerokgak Village	8°11′02″S 114°46′58″E / 8.184004°S 114.782649°E
Sanggalangit Village	8°10′56″S 114°45′47″E / 8.182315°S 114.763039°E

Materials

This study focused on *L. vannamei* aquaculture wastewater samples collected from three sampling locations. Water quality was measured *in situ* and *ex situ*. This study assessed several water quality parameters, including temperature, pH, dissolved oxygen (DO), turbidity, salinity, biological oxygen demand (BOD), nitrate, ammonia, nitrite, chemical oxygen demand (COD), and total organic matter (TOM). Table (2) shows the completeness of the instruments used to measure each of these water quality parameters.

Table 2. Instruments used for measuring wastewater quality from *L. vannamei*

Parameter	Unit	Instrument
Temperature	°C	Thermometer
pH	-	pH meter
DO	Mg/L	DO meter
Turbidity	NTU	Turbidity meter
Salinity	ppt	Refractometer
BOD	mg/L	ApHA, 23rd Edition 2017, (Section 5210.B)
Nitrate	mg/L	Spectrophotometer
Ammonia	mg/L	Spectrophotometer
Nitrite	mg/L	Spectrophotometer
COD	mg/L	SNI 6989.73:2019
Organic substances	mg/L	SNI 6989.73:2019

Data analysis

Statistical analysis

The obtained wastewater quality measurement data were then tabulated using Microsoft Excel (Microsoft, USA). The average results of wastewater quality measurements were carried out and principal component analysis (PCA) was used to determine the variation of wastewater quality parameters in the research area. The results of the analysis were then displayed in the form of tables and graphs. To make it easier to determine the quality of aquaculture wastewater, the measurement results were compared with the Decree of the Ministry of Environment of the Republic of Indonesia Number 51 of 2004 concerning seawater quality standards for marine biota.

Water pollution index

Determination of the water pollution index (WPI) of *L. vannamei* cultivation wastewater was adjusted based on the following pollution index:

$$PI_j=\sqrt{\frac{\left(\frac{Ci}{Lij}\right)^2_m+\left(\frac{Ci}{Lij}\right)^2_m}{2}}$$

Where, C_i= Concentration of water quality parameters from analysis results; L_{ij}= Concentration of water quality parameters in the designation quality standard (j); PI_j= Pollution index for designation (j); $\left(\frac{C_i}{L_{ij}}\right)_M$=Maximum Ci/Lij; and $\left(\frac{C_i}{L_{ij}}\right)_R$= Average Ci/Lij value

The categorization of pollution levels using the Water Pollution Index (WPI) is based on criteria established by **Hossain and Patra (2020)**. The WPI values are classified into four categories of pollution severity: WPI < 0.5 indicates *very good* water quality; WPI between 0.50 and 0.75 indicates *good* water quality; WPI between 0.75 and 1.0 indicates *moderately polluted* water quality; and WPI > 1.0 indicates *severely polluted* water quality.).

RESULTS

Results of measuring the quality of *L. vannamei* cultivation wastewater

The results of observations on the water quality parameters of *L. vannamei* cultivation wastewater showed varying values across locations. The temperature parameter ranged from 32.5 to 37.6 °C, which remained within the acceptable limits based on water quality standards. The highest temperature values in shrimp cultivation wastewater were recorded at Station 1, Station 2, and Station 3 in Sanggalangit Village (Table 3). An increasing temperature trend was also observed at Station 1 and Station 2 in Patas Village, as well as at Station 1, Station 2, and Station 3 in Gerokgak Village.

Table 3. Results of physicochemical measurements of *L. vannamei* cultivation wastewater quality

Village	Site	Temperature	pH	DO	Turbidity	Salinity	BOD	Ammonia	Nitrite	Nitrate	COD	Organic Substances
Patas	1	31,0^{a}	7,98^{a}	5,4^{a}	6,68^{a}	31,3^{a}	1,88^{a}	0,362^{a}	0,010^{a}	0,500^{ab}	966^{a}	53,71^{a}
	2	30,7^{a}	8,01^{a}	5,5^{a}	7,21^{a}	30,3^{a}	2,68^{a}	3,924^{b}	0,090^{a}	0,759^{b}	1220^{a}	43,20^{a}
	3	29,6^{a}	7,92^{a}	6,0^{a}	9,97^{a}	31,2^{a}	1,41^{a}	0,786^{a}	0,016^{a}	0,512^{ab}	1086^{a}	46,36^{a}
Gerogak	1	31,2^{a}	8,15^{a}	5,4a	9,07^{a}	31,3^{a}	1,88^{a}	0,156^{a}	0,001^{a}	0,505^{ab}	960^{a}	61,10^{a}
	2	31,5^{a}	8,55^{a}	5,3^{a}	6,90^{a}	31,1^{a}	1,14^{a}	0,128^{a}	0,008^{a}	0,418^{ab}	2733^{a}	44,25^{a}
	3	29,9^{a}	8,25^{a}	6,0^{a}	5,83^{a}	31,3^{a}	1,21^{a}	0,098^{a}	0,003^{a}	0,470^{ab}	1120^{a}	45,30^{a}
Sanggalangit	1	30,9^{a}	8,11^{a}	5,5^{a}	7,58^{a}	30,3^{a}	1,21^{a}	0,386^{a}	0,251^{a}	0,374^{a}	1286^{a}	30,56^{a}
	2	30,9^{a}	8,17^{a}	5,3a	2,73^{a}	30,7^{a}	1,61^{a}	0,336^{a}	0,008^{a}	0,399^{ab}	946^{a}	53,71^{a}
	3	31,3^{a}	8,24^{a}	5,6^{a}	7,27^{a}	32,1^{a}	3,62^{a}	0,545^{a}	0,040^{a}	0,479^{ab}	1700^{a}	53,71^{a}
Unit		°C	-	mg/L	NTU	ppt	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Standar		28-32	6-9	> 3	< 3	26-32	< 6	< 0.5	< 0.06	< 20	< 40	< 10

Monitoring Station 2 in Sanggalangit Village recorded an average turbidity value of 2.73 mg/L, which met the applicable quality standards. However, turbidity levels in other villages remained elevated and did not meet the wastewater quality criteria for fisheries (Table 3).

Salinity levels in this study tended to be lower than the seawater quality standards set by the Decree of the Ministry of Environment of the Republic of Indonesia Number 51 of 2004, which ranges between 26–32 ppt. The salinity of *L. vannamei* cultivation wastewater in this study ranged from 30–32 ppt, which, although within the given range, was still considered below optimal for aquaculture systems (Table 3). The highest salinity was recorded at Station 3 in Sanggalangit Village, at 32.1ppt.

The pH of *L. vannamei* cultivation wastewater in this study tended to be neutral to alkaline across all observation stations in the three villages (Table 3). According to the

Ministry's Decree, the minimum standard pH value for seawater is ≥7. The pH variations observed in this study are likely influenced by abiotic factors, particularly seasonal changes.

Dissolved oxygen (DO) levels in the wastewater varied at each sampling location. However, the DO values remained within the acceptable range for aquaculture (5–6 mg/L) at all sites. The highest DO concentrations were found at Station 3 in both Patas and Gerokgak Villages (Table 3). Based on the Decree, the minimum required DO level for wastewater is ≥3 mg/L.

Chemical Oxygen Demand (COD) represents the amount of oxygen required to chemically oxidize all organic matter in water. The highest COD values were recorded at Station 2 in Gerokgak Village (2,733 mg/L) and Station 3 in Sanggalangit Village (1,700 mg/L) (Table 3). These values far exceed the acceptable COD limit of <40 mg/L for aquaculture wastewater, indicating poor water quality. Reducing COD levels remains a critical need for improving *L. vannamei* cultivation wastewater quality.

Nitrate concentrations in the cultivation wastewater exceeded the permissible limit of 20 mg/L. The highest nitrate concentration was observed at Station 2 in Patas Village (0.759 mg/L), followed by Station 1 in Gerokgak Village (0.505 mg/L), and Station 3 in Sanggalangit Village (0.479 mg/L) (Table 3). Although these values are numerically below the stated threshold, the sentence implies a discrepancy, with a recommendation to confirm the actual standard. Elevated nitrate levels in wastewater can negatively impact water quality and aquatic ecosystems.

Ammonia levels were also the highest at Station 2 in Patas Village, reaching 3.054mg/ L, significantly higher than those recorded at other stations. Similarly, organic matter levels exceeded the threshold of <10 mg/L, as set by the Ministry's Decree. The highest organic substance concentration was recorded at Station 1 in Gerokgak Village, reaching 61.10mg/ L (Table 3).

Water pollution index (WPI)

The water pollution index (WPI) for *L. vannamei* cultivation wastewater in this study indicated that all observation stations were classified as heavily polluted, as shown in Fig. (2). The highest WPI value was observed at Station 3 in Patas Village during the April 2024 sampling period, with a WPI of 4.30 (WPI > 1), indicating a severe level of pollution.

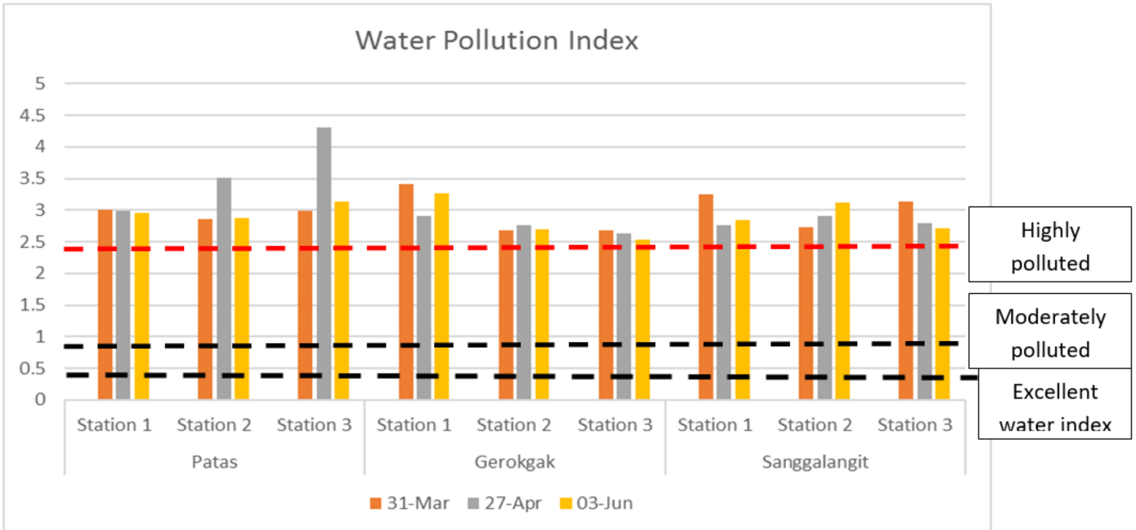

Fig. 2. Water pollution index (WPI) of wastewater of *L. vannamei* on this study. Description: WPI value based on 4 categories of pollution levels including: WPI<0.5 (very good water quality); WPI 0.50 – 0.75 (good water quality); WPI 0.75 – 1 (moderately polluted water quality); and WPI>1 (severely polluted water quality) **(Hossain & Patra, 2020)**.

Correlation of water quality parameters

A total of ten water quality parameters (organic matter, salinity, BOD, nitrate, turbidity, ammonia, nitrite, COD, pH, and temperature) were used for principal component analysis (Fig. 3). Values exceeding 1.0 were considered significant. The results of PCA analysis can assist in grouping sampling locations based on similarities in environmental parameters or species composition.

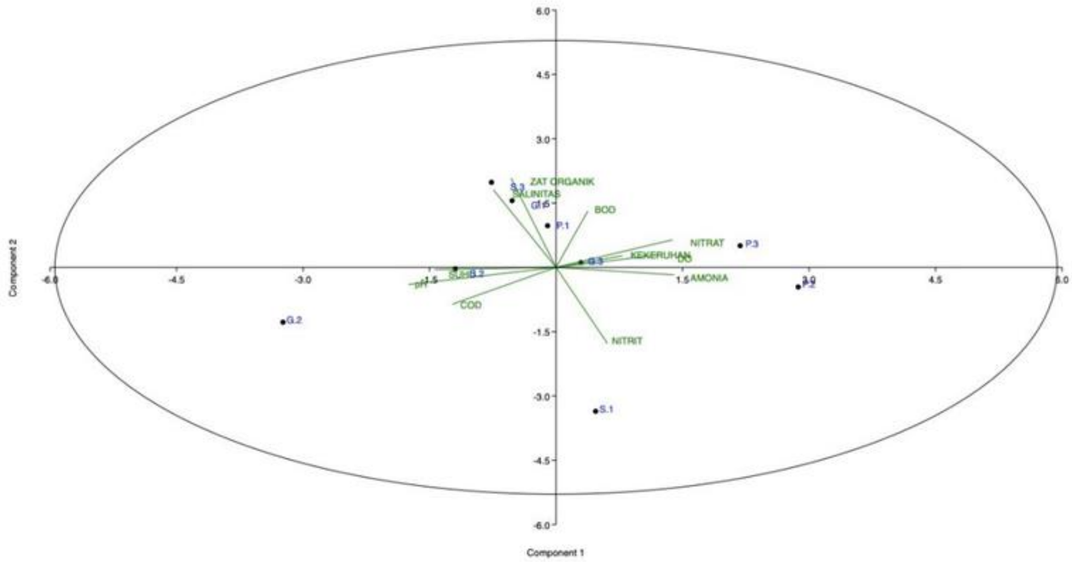

Fig. 3. Results of principal component analysis (PCA) of *L. vannamei* wastewater quality parameters.

Group G1 and P1 from the results of the clatring analysis had a similarity value of 99.22%, because at both stations, the most influential factors were recorded to be salinity and BOD. G2 and P3 from the results of the clustering analysis had a similarity value of 98.37%, because at both stations, the most influential factors are nitrate and DO parameters. Furthermore, G2 had the farthest similarity value with other stations since it can be seen that this station had the highest pH, temperature, and COD values compared to other stations. Group G1 and P1 from the results of the clatring analysis have a similarity value of 99.22%, because at both stations the most influential factors are salinity and BOD. G2 and P3 from the results of the clustering analysis had a similarity value of 98.37%, because at both stations, the most influential factors are nitrate and DO parameters. Furthermore, G2 had the farthest similarity value with other stations, because it can be seen that, this station has the highest pH, temperature, and COD values compared to other stations. This, in turn, may cause this station to stand alone in the clustering analysis.

DISCUSSION

The highest temperature values in this study ranged from 31.0 to 32.5°C, which exceeded the maximum allowable temperature range of 28– 30°C set by the Decree of the Ministry of Environment of the Republic of Indonesia Number 51 of 2004 concerning seawater quality standards for marine biota. Temperature fluctuations can influence the adaptability of various microorganisms. As the temperature in wastewater changes, it may alter the composition and abundance of microbial communities in the aquatic environment **(Lin *et al.*, 2016)**. Furthermore, waste disposal from aquaculture systems can have major environmental implications on seawater temperature **(Akinnawo, 2023)**.

This phenomenon is especially true for intensive to super-intensive cultivation systems that use high stocking densities with constant circulating water, causing the temperature of the discharged wastewater to be higher than the temperature of the surrounding water **(Vinatea *et al.*, 2010)**. This naturally causes thermal pollution in marine water bodies, which is defined as a rise in water temperature over the typical range for that habitat **(Hamdhani *et al.*, 2020)**. Thermal pollution can be harmful to the aquatic environment and marine biota. Increased water temperature, for example, may reduce the amount of dissolved oxygen in the water that is essential for aquatic biota and can lead to increased metabolism **(Rajesh & Rehana, 2022)**. Furthermore, high water temperatures can have detrimental effects on the development and reproduction of aquatic life since they may have difficulty adapting to extreme temperatures **(Mugwanya *et al.*, 2022)**. Furthermore, increased water temperatures caused by the discharge of aquaculture waste can affect species composition and biodiversity.

Turbidity is a measure of water transparency, reflecting the amount of light absorbed or scattered by suspended particles such as soil, silt, and microbes that affect water clarity. Turbidity is very important for the long-term growth of aquatic ecosystems and biodiversity conservation **(Lin *et al.*, 2023)**. The level of turbidity in shrimp wastewater can be influenced by solids that cannot be dissolved in water affecting the biomass of organic matter accumulated in the waste **(Jefri *et al.*, 2020)**. The turbidity of wastewater generally increase with the number of shrimp raised and water changes **(Rangka & Gunarto, 2012; Guo *et al.*, 2022)**. Conversely, the decrease in turbidity values in this study may be ascribed to the regular water change cycle carried out by farmers to reduce the accumulation of organic matter in the cultivation waste **(Mishra *et al.*, 2023)**.

Fluctuations in salinity levels in wastewater are influenced by climate factors. Salinity levels tend to decrease because of the condition of the cultivation environment when sampling was carried out in the rainy season. Rainfall and mixing with fresh water/rivers can reduce salinity since fresh water can dilute the salt content in seawater, thereby reducing its concentration **(Kaushal *et al.*, 2021)**. A decrease in salinity that lasts for more than a few hours can affect the physiology of aquatic biota in the marine environment **(Röthig *et al.*, 2023)**. Furthermore to the marine environment, shrimp waste that still has high salinity can also have an impact on local ecology, especially agricultural land **(Lan, 2013)**. Salinity also increases as the distance between shrimp ponds and agricultural land increases. Case studies showed that every one meter decrease in distance between shrimp ponds and surrounding agricultural land causes soil salinity to increase by up to 0.14% **(Johnson *et al.*, 2016)**.

The pH value range certainly varies in cultivation wastewater due to the influence of abiotic factors, especially the season. However, the optimal pH range recommended for cultivation wastewater is 6.5 - 9.0 when discharged into the environment **(Wiradana *et al.*, 2023)**. Farmers may be able to control the alkalinity of the pH of shrimp wastewater by ozonation containing sodium bicarbonate-based lime and hydrated lime, thereby increasing the efficiency of $CaCO_3$ as an alkalinity supplement **(Whangchai *et al.*, 2004)**.

Dissolved oxygen (DO) levels in *L. vannamei* cultivation wastewater were strongly influenced by shrimp stocking density. In intensive systems, high stocking densities increase oxygen demand due to heightened shrimp metabolism, which can lead to a decrease in DO levels in the pond water. However, DO levels can be maintained within optimal ranges by using windmills or wave generators that enhance aeration and provide oxygen that can be directly utilized by *L. vannamei*. Additionally, phytoplankton contribute to increased DO through photosynthesis by utilizing CO_2 from water and the atmosphere and producing O_2 **(Mahenda *et al.*, 2021; Sani *et al.*, 2022)**.

Previous studies have also shown that increased phytoplankton populations in intensive *L. vannamei* systems lead to higher DO concentrations and support microbial communities. Intensive systems tend to promote the proliferation of both phytoplankton and heterotrophic bacteria, contributing positively to environmental productivity **(Furtado *et al.*, 2015)**. However, despite these benefits, it remains essential to control DO levels through proper wastewater treatment to prevent algal blooms in coastal areas.

High chemical oxygen demand (COD) levels can lower DO in surrounding water bodies, negatively impacting aquatic ecosystems near shrimp ponds **(Ali *et al.*, 2022)**. Integrated cultivation systems combining shrimp with shellfish and macrophyte algae have been developed as sustainable alternatives. In Romania, seaweed was found to reduce COD levels by up to 29% in shrimp wastewater **(Iber & Kasan, 2021)**. Similarly, the use of *Chlorella vulgaris* in a combined fermentation and microalgae system reduced COD by up to 94.4% in mariculture wastewater **(Zhang *et al.*, 2021)**.

Nitrate levels, when elevated, can lead to eutrophication, accelerating the growth of aquatic plants and invasive species in river environments **(Bayrakli, 2023; Napoletano *et al.*, 2023)**. Although nitrate itself is not toxic, it can be converted to nitrite, which may react with amines to form harmful compounds such as N-nitrosamines, and potentially cause methemoglobinemia in infants **(Nakagawa *et al.*, 2024)**. To address this, bioremediation technologies are needed. For example, *Synechocystis* sp. PCC 6803 (ΔSphU) cyanobacteria were shown to reduce nitrate levels in shrimp wastewater by up to 80.10% **(Krasaesueb *et al.*, 2019)**. Constructed wetlands have also been effective for reducing ammonium and nitrate in aquaculture effluents **(Bhatt *et al.*, 2024)**.

Nitrogen cycling involves interactions among microorganisms, aquatic plants, and aquaculture waste, especially through nitrite and nitrate pathways **(Iammarino *et al.*, 2013)**. High nitrite levels in wastewater can permanently react with hemoglobin to form methemoglobin, disrupting oxygen transport in aquatic organisms. Moreover, nitrite ingestion by humans may result in the formation of carcinogenic N-nitrosamines **(Chen *et al.*, 2016)**.

Ammonia (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) serve as nitrogen sources that benefit phytoplankton productivity, potentially increasing DO and providing natural food for shrimp. However, excess ammonia can be toxic to *L. vannamei* **(Zhao *et al.*, 2020)**. Ammonia is oxidized by bacteria into nitrite and then nitrate through the nitrification process. In this study, the high ammonia levels observed at Station 2 in Patas Village were likely due to the accumulation of uneaten feed and shrimp feces. Ammonia primarily originates from the decomposition of nitrogen-rich organic waste, including feed and excreta **(Burford & Williams, 2001)**. Ammonia stress has been shown to reduce gut microbial diversity and alter the bacterial composition of *L. vannamei*, affecting genera such as *Bacteroides*, *Enterococcus*, *Faecalibacterium*, *Nautella*, *Pseudoalteromonas*, *Tenacibaculum*, and *Weissella* **(Duan *et al.*, 2024)**. Because of these impacts, ammonia is considered a key indicator of water quality, and its associated stress contributes significantly to disease outbreaks **(Kamaruddin *et al.*, 2021)**.

The findings of this study are consistent with earlier research, which reported that WPI values for shrimp ponds using super-intensive systems in Situbondo fell within the moderately polluted category **(Mahmudi *et al.*, 2022)**. In recent years, several studies have modeled pollution from aquaculture wastewater to assess its impact **(Lu *et al.*, 2009; He *et al.*, 2011)**, though limited research has applied the water pollution index (WPI) directly to measure cultivation waste impacts.

Research in Jembrana Regency, where *L. vannamei* effluent was discharged through coastal wastewater channels, also indicated moderate to heavy pollution levels after 80 and 110 days of cultivation **(Sumantra *et al.*, 2022)**. One major source of pollution is the routine release of wastewater during daily water exchanges and harvests. This discharge contains high levels of nutrients, suspended solids, and organic matter that reduce DO and increase turbidity **(Barraza-Guardado *et al.*, 2013; Cardoso-Mohedano *et al.*, 2016)**. Elevated WPI values can also alter the coastal morphological balance, particularly when coupled with tidal oscillations **(Roversi *et al.*, 2020)**. Factors such as location, management practices, and stocking density play a critical role in determining shrimp pond wastewater quality **(Bull *et al.*, 2021)**.

Further research is needed to develop environmentally friendly and efficient aquaculture wastewater treatment technologies that can improve effluent quality and protect aquatic ecosystems **(Martínez-Córdova *et al.*, 2011)**. Regular monitoring of physical, chemical, and biological water quality parameters is crucial—not only for predicting and controlling pond conditions but also for minimizing environmental degradation and optimizing production outcomes **(Ferreira *et al.*, 2011; González-Vera & Brown 2017; Khoa *et al.*, 2020)**.

Several studies have also employed principal component analysis (PCA) to analyze water quality and minimize large environmental datasets. PCA has proven effective in identifying key variables linked to eutrophication in tropical lake systems **(Parinet *et al.*, 2004)**. In the current study, PCA was applied to parameters including temperature, pH, DO, turbidity, salinity, BOD, nitrate, ammonia, nitrite, COD, and organic substances. These variables are considered essential for assessing environmental conditions in *L. vannamei* aquaculture.

CONCLUSION

Aquaculture activities that implement intensive cultivation systems can significantly increase the waste load discharged into the aquatic environment, posing challenges to the sustainability of these operations. In this study, parameters such as temperature, turbidity, DO, BOD, COD, nitrate, nitrite, ammonia, and organic substances were found to increase at several observation stations. The WPI values indicated that all stations were classified as heavily polluted, with the highest WPI values recorded at Station 3 in Patas Village.

Results from the PCA revealed that pH, temperature, and COD were the most influential factors affecting the quality of *L. vannamei* pond wastewater overall. These findings demonstrate that intensive *L. vannamei* cultivation systems contribute significantly to increased wastewater pollution in the natural environment.

Therefore, it is strongly recommended that wastewater treatment plants be implemented to ensure that the quality of effluents discharged into aquatic ecosystems remains within acceptable environmental standards.

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