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Water Quality Dynamics and Multivariate Analysis of Shrimp Production in Super-Intensive *Litopenaeus vannamei* Culture

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Abstract

Water quality stability is a key determinant of ecological balance and production performance in super-intensive shrimp aquaculture systems. This study evaluated the dynamics of major water quality parameters and identified the environmental drivers influencing shrimp production using multivariate analysis. The study was conducted in three super-intensive ponds of whiteleg shrimp (Litopenaeus vannamei) over a 61-day culture period. Water quality parameters including pH, temperature, salinity, and dissolved oxygen (DO) were monitored periodically, while shrimp production indicators such as survival rate (SR), average body weight (ABW), specific growth rate (SGR), and feed input were recorded. The results showed that pH and salinity were significantly influenced by measurement time, whereas temperature and DO remained relatively stable and showed no significant spatial differences among ponds. The observed pH ranged from 7.61 to 8.89 (mean 8.32 ± 0.21), temperature averaged 29.4 ± 1.15 °C, salinity ranged from 15 to 30 g L^{-1}, and DO varied between 4.7 and 8.5 mg L^{-1}, indicating generally suitable conditions for shrimp culture. Principal component analysis identified three components explaining 72.27% of the total variance. The first component represented the main productivity gradient associated with DO, feed input, ABW, salinity, and survival rate. The second component reflected physicochemical environmental variability dominated by temperature and pH, while the third component was primarily associated with shrimp growth dynamics represented by SGR. These results highlight the strong interaction between environmental stability and shrimp production performance, emphasizing the importance of integrated water quality management in super-intensive shrimp culture systems.

Keyword: *Litopenaeus vannamei*;; principal component analysis; shrimp production; super-intensive culture; water quality dynamics

INTRODUCTION

Shrimp aquaculture has become one of the fastest-growing sectors of global seafood production, with whiteleg shrimp *Litopenaeus vannamei* emerging as one of the most important cultured species due to its rapid

growth, high market demand, and adaptability to intensive culture systems (Boyd *et al*., 2020; Naylor *et al*., 2021; Huang *et al*., 2024). In response to increasing global demand and limitations in land and water resources, shrimp farming has progressively shifted toward intensive and super-intensive production systems designed to maximize productivity per unit area (Boyd *et al*., 2022; Villarreal and Juarez, 2022; Verdegem *et al*., 2023). In Indonesia, vannamei shrimp culture is conducted across various technological levels, ranging from traditional low-density systems to highly controlled super-intensive systems characterized by high stocking densities, intensive feeding regimes, and continuous aeration (Boyd *et al*., 2022; Villarreal and Juarez, 2022;Supono and Rivaie, 2025)

In super-intensive culture systems, shrimp are typically reared in relatively small culture units, often less than 2000 m², using concrete tanks or high-density polyethylene (HDPE)-lined ponds to enable precise environmental control and high stocking densities (Brune, 2021; Reis *et al*., 2022; Mustafa *et al*., 2024). These systems enable improved environmental control and production efficiency; however, the high stocking densities also increase organic loading, nutrient accumulation, and environmental sensitivity within the pond ecosystem (Khanjani *et al*., 2022; Le *et al*., 2025; Matishov *et al*., 2025; Rana and Ray, 2025). As a consequence, maintaining environmental stability becomes a critical factor in sustaining shrimp health, growth performance, and survival (Boyd *et al*., 2020; Raza *et al*., 2024; Le *et al*., 2025; Halim *et al*., 2026).

Among the environmental factors influencing shrimp production, water quality plays a central role in regulating biological, chemical, and microbial processes in aquaculture ponds. Key water quality parameters such as dissolved oxygen (DO), temperature, salinity, and pH are fundamental drivers of shrimp physiological performance and ecosystem processes. Dissolved oxygen supports shrimp respiration and aerobic microbial metabolism responsible for organic matter degradation and nutrient cycling. Temperature regulates metabolic and enzymatic activity, while salinity controls osmotic balance and ion regulation in shrimp. Meanwhile, pH dynamics are closely associated with carbonate equilibrium and photosynthesis–respiration processes that regulate carbon dioxide concentrations in pond water (Boyd *et al*., 2020; Zhang *et al*., 2022; Liu *et al*., 2026).

In intensive aquaculture systems, these environmental parameters rarely operate independently. Instead, they interact dynamically through a network of physical, chemical, and biological processes within the pond ecosystem. For example, phytoplankton photosynthesis can simultaneously increase pH and dissolved oxygen concentrations, whereas microbial respiration and organic matter decomposition may decrease oxygen levels and alter carbonate chemistry (Kim and Lee, 2009; Piwosz *et al*., 2020; Moreno *et al*., 2024). Temperature variations may influence oxygen solubility and microbial metabolism, while salinity fluctuations can modify microbial community composition and nutrient transformation processes (Liu *et al*., 2025; Hu *et al*., 2026; Xiong *et al*., 2026). Such interactions create complex environmental dynamics that can influence shrimp growth, survival, and overall pond productivity (Wiyoto *et al*., 2022; Ariadi *et al*., 2025; Li *et al*., 2025).

Despite the importance of these interactions, conventional monitoring in shrimp culture systems often evaluates water quality parameters individually using threshold-based criteria. Although this approach is useful for operational management, it does not fully capture the complex relationships and co-variability among multiple environmental variables. As a result, underlying environmental gradients that influence pond ecosystem stability and shrimp production may remain undetected (Musa *et al*., 2023; Do *et al*., 2025; Tangoi *et al*., 2025).

Multivariate statistical techniques, particularly Principal Component Analysis (PCA), provide a powerful approach for analyzing complex environmental datasets by reducing multidimensional variables into a smaller number of principal components while retaining most of the original data variability (Jolliffe and Cadima, 2016; Wiyoto and Effendi, 2020). PCA has been widely applied in environmental and aquaculture studies to identify dominant environmental drivers, reveal relationships among water quality parameters, and simplify the interpretation of ecosystem variability (Zhang *et al*., 2020; Liu et al., 2024; Munjayana *et al*., 2024). Previous studies have demonstrated that PCA can effectively highlight key environmental gradients influencing aquaculture water quality and production performance, thereby supporting more informed environmental management strategies.

However, despite increasing interest in multivariate environmental analysis, there remains a limited number of studies that specifically apply PCA to examine the integrated dynamics of core water quality parameters—particularly dissolved pH, temperature, salinity, and oxygen, —in super-intensive shrimp grow-out systems. Many existing studies focus primarily on descriptive analyses of individual parameters rather than exploring the multivariate structure of environmental variability that may drive production performance and ecosystem stability.

Therefore, this study aimed to evaluate the dynamics of key water quality parameters in super-intensive *L. vannamei* culture ponds and to identify the dominant environmental drivers influencing shrimp production using PCA. Specifically, this study aimed to (i) describe the temporal dynamics of major water quality parameters during the culture cycle, (ii) analyze the relationships among these parameters using correlation and PCA loadings, and (iii) identify the principal components that explain the dominant patterns of water

quality variability in super-intensive shrimp culture systems. Understanding these relationships is expected to provide an integrated perspective on water quality dynamics and contribute to improved environmental monitoring and management strategies in intensive shrimp aquaculture.

MATERIALS AND METHODS

Location and time of research

The study was conducted over a period of two months at Raci Shrimp Farm Unit 3, Bangil, East Java.

Experimental design

Preparation of culture units and rearing media

The culture units used for Pacific whiteleg shrimp *L. vannamei*) farming consisted of three super-intensive ponds (Petak A, Petak B, and Petak C), each with an area of 700 m² and a water depth of 1.2 m. Prior to stocking, the ponds were disinfected by spraying chlorine at a dose of 5 mL ton^{-1}. This was followed by thorough cleaning of the pond walls and bottom. The surfaces were carefully scrubbed using abrasive pads to avoid damaging the plastic lining, while being rinsed with freshwater until clean. The ponds were then re-sprayed with chlorine at the same dosage (5 mL ton^{-1}) and left to dry for two to three days. Subsequently, liming was applied to the pond walls at a dose of 5 mg L^{-1}, followed by sun-drying

Preparation of the rearing media involved the use of equipment such as water pumps, water filters, drums, and an ATC refractometer. The materials used included water, chlorine, probiotics, and lime. Water was sourced from a bore well with a salinity range of 15–25 g L^{-1}. Six paddlewheel aerators (SL Vaname, 1 HP) were installed in each pond, arranged to generate a clockwise water circulation.

Post-larvae stocking

The post-larvae (PL) were obtained from a commercial hatchery in East Java. The shrimp used were specific pathogen-free (SPF), uniform in size, actively swimming, and physically intact. PL8 shrimp were stocked at a density of 500 shrimps m^{-2}. Stocking was carried out in the morning, preceded by a 30-minute acclimatization process to adjust the shrimp to pond temperature conditions. Random sampling was conducted by taking two bags of post-larvae to verify that the number received matched the quantity ordered.

Feed Management

Commercial feed containing approximately 35% protein was provided according to shrimp age and biomass. During DOC 1–30, feed size 922-0 was used following a blind feeding method. For DOC 31–40, feed size 922-1 was applied, and for DOC 41–70, feed size 922-2 was used. Feeding frequency during DOC 1–30 was three times daily at 07:00, 12:00, and 16:00 (WIB). From DOC 31 until harvest, feed was administered at 3–5% of total biomass, with a feeding frequency of four times daily at 07:00, 12:00, 16:00, and 21:00 (WIB).

Water quality

Daily water quality parameters measured included pH, temperature, salinity, and dissolved oxygen. Measurements were conducted six times per day at 05:00, 08:00, 11:00, 14:00, 17:00, and 20:00 (WIB).
Water pH was measured using a pH meter (Hanna), temperature using a thermometer, salinity using an ATC refractometer, and dissolved oxygen using a Lutron DO-5510HA DO meter.

Data Analysis

Data were tabulated using Microsoft Excel 365 and subsequently analyzed using repeated measures analysis of variance (ANOVA) followed by Duncan's Multiple Range Test (DMRT) as a post hoc analysis. Principal Component Analysis (PCA) was applied to identify patterns and relationships among variables. All statistical analyses were performed using SPSS version 23 with a confidence level of 95%.

RESULTS

Water Quality Parameter

pH

The fluctuation in pH values was significantly influenced by the time of measurement ($p < 0.05$; $p = 0.000$), whereas no significant differences were detected among pond plots ($p = 0.68$). The observed pH values ranged from 7.61 to 8.89, with daily fluctuations varying between 0.03 and 0.90. The overall mean pH was 8.32 ± 0.21 (Figure 1). These results indicate that temporal variation played a more dominant role than spatial variability in shaping pH dynamics within the culture ponds. The relatively narrow range of pH values suggests that the water quality remained within the acceptable limits for shrimp culture during the observation period.

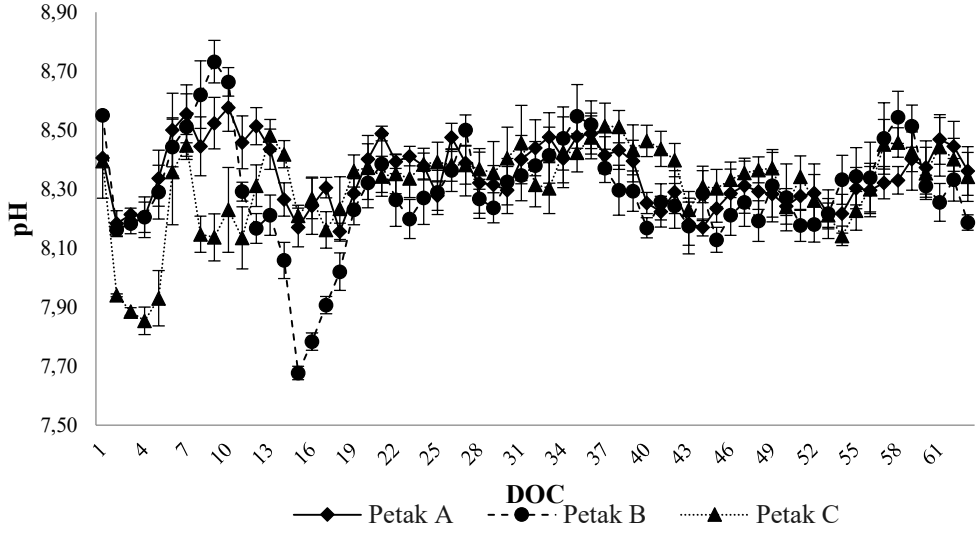


Figure 1. pH values in ponds A, B, and C during the super-intensive culture of Pacific whiteleg shrimp *L. vannamei* at a stocking density of 500 shrimps m^{-2} over a 61-day culture period.

Temperature

Water temperature was not significantly affected by the time of measurement ($p = 0.732$), and no significant differences were observed among ponds ($p = 0.993$). The recorded temperature showed daily fluctuations ranging from 3.0 to 3.2 °C, with an overall mean of 29.4 ± 1.15 °C (Figure 2). Temperature values remained relatively consistent throughout the observation period, with only minor temporal variations recorded during the culture cycle. The distribution of temperature measurements among ponds A, B, and C showed a similar pattern over time, indicating relatively uniform thermal conditions across the culture system during the 61-day rearing period.

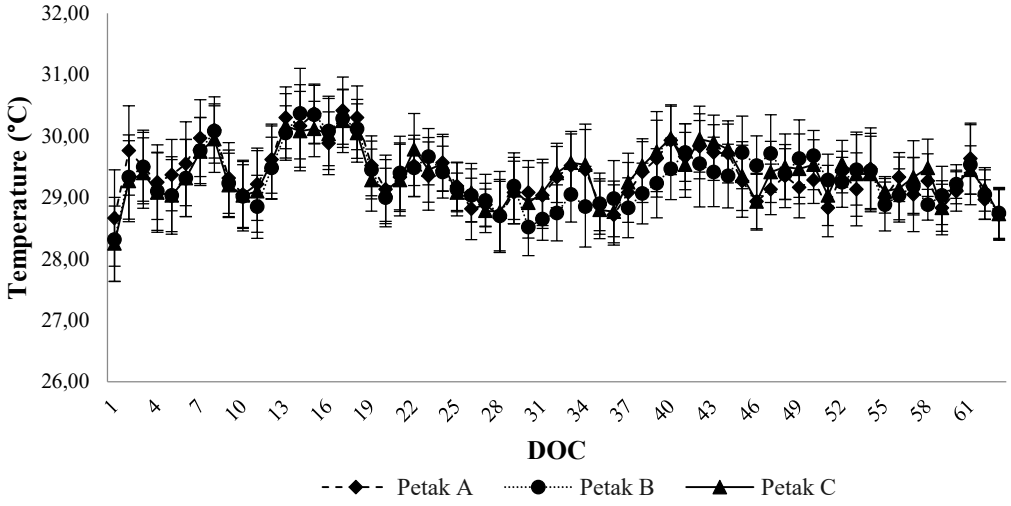


Figure 2. Temperature profiles in ponds A, B, and C during a 61-day super-intensive culture period of Pacific whiteleg shrimp *L.vannamei* at a stocking density of 500 shrimps m^{-2}.

Salinity

Salinity was significantly influenced by the time of measurement ($p = 0.000$). Salinity values in ponds B and C were similar and were both significantly higher than those in pond A ($p = 0.007$). The salinity in ponds B and C ranged from 15 to 30 g L^{-1}, whereas pond A ranged from 15 to 26 g L^{-1}. Overall, the salinity values showed temporal variability throughout the culture period. Despite these variations, the salinity levels among the ponds remained within a relatively comparable range during the observation period. The distribution of

salinity measurements indicated a consistent pattern in ponds B and C, while pond A exhibited a slightly narrower salinity range during the monitoring period.

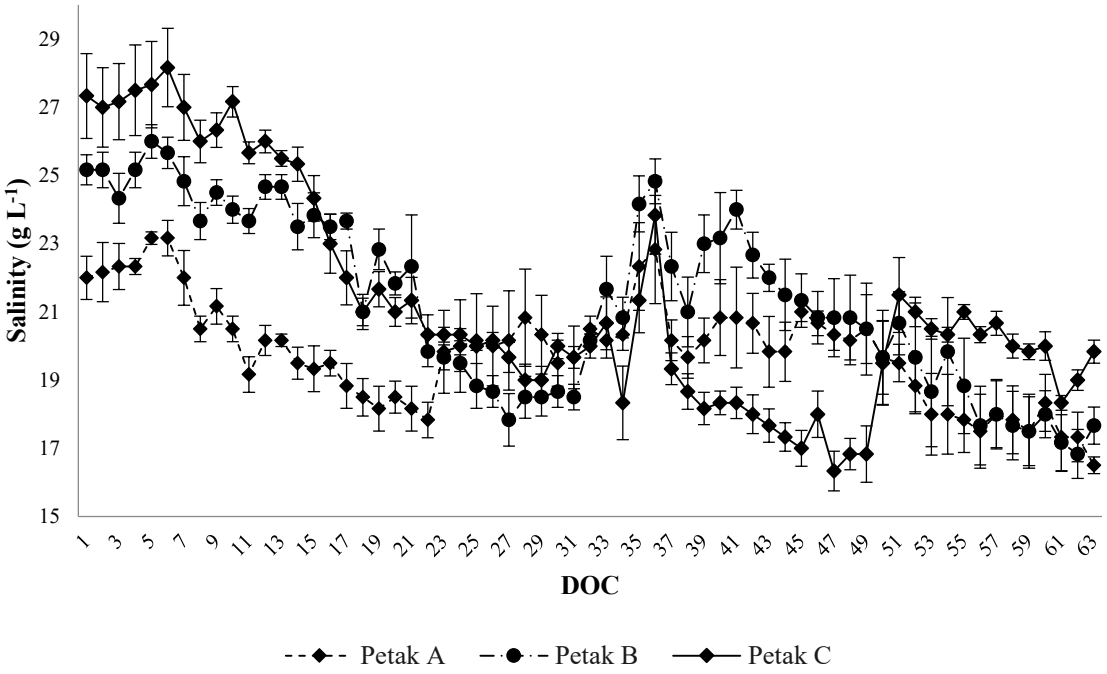


Figure 3. Salinity levels in ponds A, B, and C during a 61-day super-intensive culture period of Pacific whiteleg shrimp *L. vannamei* at a stocking density of 500 shrimps m^{-2}.

Dissolved oxygent

Dissolved oxygen (DO) was not significantly influenced by the time of measurement ($p = 0.41$), and no significant differences were observed among ponds ($p = 0.589$). The dissolved oxygen concentrations ranged from 4.7 to 8.5 mg L^{-1}. Overall, DO values remained relatively stable throughout the observation period Figure 4). The measurements across ponds A, B, and C showed a similar pattern over time, indicating relatively uniform oxygen conditions among the culture units during the monitoring period.

Principal component analysis identified three principal components with eigenvalues greater than 1, explaining 72.27% of the total variance in the dataset. The first principal component (PC1) accounted for 42.16% of the variance, indicating that this component represented the dominant source of variability among the measured parameters. The second (PC2) and third (PC3) components explained 16.22% and 13.89% of the total variance, respectively. Together, these three components captured the majority of the variability in the dataset, while the remaining components contributed relatively minor proportions of variance and were therefore not considered for further interpretation according to the Kaiser criterion.

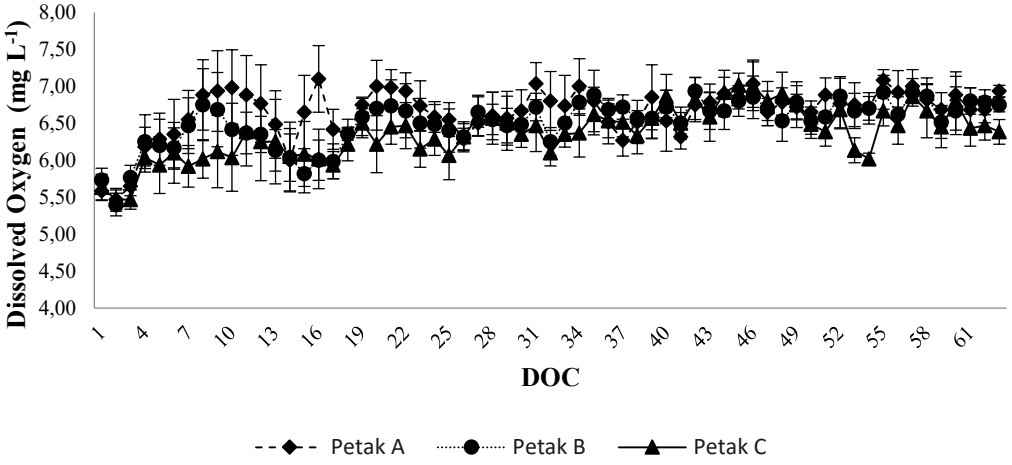


Figure 4. Dissolved oxygen dynamics in ponds A, B, and C during a 61-day super-intensive culture period of Pacific whiteleg shrimp *Litopenaeus vannamei* at a stocking density of 500 shrimps m^{-2}.

Principal component analysis

Principal component analysis identified three principal components with eigenvalues greater than 1, explaining 72.27% of the total variance in the dataset (Table 1). The first principal component (PC1) accounted for 42.16% of the variance, indicating that this component represented the dominant source of variability among the measured parameters. The second (PC2) and third (PC3) components explained 16.22% and 13.89% of the total variance, respectively. Together, these three components captured the majority of the variability in the dataset, while the remaining components contributed relatively minor proportions of variance and were therefore not considered for further interpretation according to the Kaiser criterion.

Table 1. Variance of each principal component based on eigenvalue analysis of the correlation matrix for water quality parameters in ponds A, B, and C during a 61-day super-intensive culture of Pacific whiteleg shrimp *Litopenaeus vannamei* at a stocking density of 500 shrimps m^{-2}

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.373	42.158	42.158	3.373	42.158	42.158
2	1.298	16.222	58.380	1.298	16.222	58.380
3	1.111	13.894	72.274	1.111	13.894	72.274
4	.756	9.451	81.724			
5	.607	7.592	89.316			
6	.430	5.374	94.690			
7	.304	3.797	98.487			
8	.121	1.513	100.000			

Extraction Method: Principal Component Analysis.

The Kaiser–Meyer–Olkin (KMO) value was 0.636, indicating an acceptable sampling adequacy for principal component analysis (Table 2). Bartlett's test of sphericity was highly significant ($\chi^2 = 616.879$, df = 28, $p < 0.001$), demonstrating that the correlation matrix was suitable for factor extraction. These results confirm that the dataset was appropriate for further analysis using PCA.

Table 2. The Kaiser–Meyer–Olkin (KMO) and Bartlett's test for water quality parameters in ponds A, B, and C during a 61-day super-intensive culture of Pacific whiteleg shrimp *Litopenaeus vannamei* at a stocking density of 500 shrimps m^{-2}

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.636
Bartlett's Test of Sphericity	Approx. Chi-Square	616.879
	df	28
	Sig.	.000

Principal component analysis identified three principal components that explained the major variability in the dataset. The interpretation of each component was based on the magnitude of the loading values for each variable. The PC1 showed strong loadings for dissolved oxygen (0.760), average body weight (0.770), feed input (0.643), salinity (-0.788), and survival rate (-0.908). This component appears to represent a production–environment interaction factor, where shrimp growth and feeding performance are associated with key environmental conditions in the pond. The positive loadings of DO, feed, and ABW indicate that higher oxygen availability and feed input were associated with improved shrimp growth performance. Conversely, the negative loadings of salinity and survival rate suggest that variations in salinity may influence shrimp survival dynamics within the culture system. Overall, PC1 likely reflects the main productivity gradient of the shrimp pond ecosystem, linking environmental conditions with shrimp production performance.

The PC2 was mainly influenced by temperature (0.672), and pH (-0.759). This component appears to represent a physicochemical environmental gradient. Temperature showed the strongest positive loading in this component, indicating that thermal conditions played an important role in shaping variations among samples. The negative loading of pH suggests that variations in temperature may influence carbonate balance and biological activity in the pond system.

The PC3 was dominated by SGR (0.737) and temperature (0.507). This suggests that PC3 represents a growth-related factor, particularly reflecting the relationship between environmental conditions and shrimp growth rate. The strong loading of SGR indicates that this component is primarily associated with shrimp growth performance, possibly influenced by metabolic responses to environmental conditions such as temperature. This component likely reflects environmental variability associated with thermal and chemical dynamics in the culture ponds.

Table 3. Component matrix derived from Principal Component Analysis (PCA) showing the loadings of water quality parameters, feeding variables, and shrimp growth performance in super-intensive shrimp aquaculture systems

Component Matrix[a]

	Component		
	1	2	3
pH	.329	-.759	.318
Temperature	-.306	.672	.507
Salinity	-.788	-.017	-.304
DO	.760	-.088	.297
SR	-.908	-.073	.035
Feed	.643	.482	.034
ABW	.770	.125	-.167
SGR	-.374	-.097	.737

Extraction Method: Principal Component Analysis.

The anti-image correlation matrix showed that most variables had Measure of Sampling Adequacy (MSA) values greater than 0.50, indicating their suitability for inclusion in the principal component analysis (Table 4). Only temperature showed a relatively lower MSA value, suggesting weaker correlations with other variables. Overall, these results indicate that the dataset was appropriate for PCA.

The results showed that most variables had MSA values above the commonly accepted threshold of 0.50, indicating that they were suitable for inclusion in the PCA model. Variables such as salinity, DO, ABW, SGR, SR, and feed input demonstrated adequate sampling adequacy, suggesting that these variables contributed meaningfully to the correlation structure of the dataset.

In contrast, temperature exhibited a relatively low MSA value (<0.50), indicating that this variable had weaker correlations with the other variables in the dataset. Variables with low MSA values may have limited contribution to the factor structure and can sometimes reduce the robustness of the PCA model. However, depending on the ecological or experimental importance of the variable, it may still be retained for interpretative purposes.

Overall, the anti-image matrix results indicate that the dataset meets the assumptions required for principal component analysis, as most variables show sufficient sampling adequacy. This supports the validity of the PCA results in identifying the main components explaining variability among environmental parameters and shrimp production indicators.

Table 4. Anti-image matrices (covariance and correlation) showing measures of sampling adequacy (MSA) for variables used in Principal Component Analysis (PCA), including water quality parameters (pH, temperature, salinity, dissolved oxygen) and production indicators (SR, feed, ABW, and SGR) in a super-intensive shrimp culture system.

Anti-image Matrices

	pH	Suhu	Salinitas	DO	SR	Pakan	ABW	SGR
pH	.728	.158	.019	-.203	.027	.102	.058	-.088

Anti-image Covariance	Temperature	.158	.655	.133	.017	-.156	-.195	-.063	-.188
	Salinity	.019	.133	.401	.180	-.122	-.109	.026	.014
	DO	-.203	.017	.180	.476	-.012	-.141	-.009	.058
	SR	.027	-.156	-.122	-.012	.191	.175	.161	.053
	Feed	.102	-.195	-.109	-.141	.175	.424	.102	.112
	ABW	.058	-.063	.026	-.009	.161	.102	.401	.131
	SGR	-.088	-.188	.014	.058	.053	.112	.131	.818
Anti-image Correlation	pH	.590[a]	.229	.036	-.345	.073	.184	.107	-.114
	Temperature	.229	.360[a]	.260	.031	-.440	-.370	-.123	-.257
	Salinitas	.036	.260	.723[a]	.412	-.443	-.266	.065	.024
	DO	-.345	.031	.412	.754[a]	-.040	-.315	-.020	.092
	SR	.073	-.440	-.443	-.040	.622[a]	.616	.581	.133
	Feed	.184	-.370	-.266	-.315	.616	.527[a]	.247	.190
	ABW	.107	-.123	.065	-.020	.581	.247	.723[a]	.228
	SGR	-.114	-.257	.024	.092	.133	.190	.228	.607[a]

a. Measures of Sampling Adequacy(MSA)

Discussion

The water quality conditions observed in this study indicate that the culture environment remained within suitable limits for the super-intensive culture of *L. vannamei*. The relatively stable pH values within the optimal range (7.5–8.5) suggest that the carbonate buffering capacity of the pond water was sufficient to moderate diel fluctuations driven by biological activity. In aquaculture ponds, pH dynamics are strongly linked to the balance between phytoplankton photosynthesis and respiratory processes of shrimp, bacteria, and other microorganisms. During daylight, photosynthetic CO_2 uptake elevates pH, whereas nighttime respiration and microbial decomposition increase CO_2 concentrations and reduce pH. These diel processes are characteristic of productive shrimp ponds and represent a key indicator of biological activity and nutrient cycling within the system (Moriarty, 1997; Boyd *et al*., 2020; Zhang *et al*., 2022; Yusoff *et al*., 2024).

The stability of temperature recorded in this study further supports the observed environmental balance. Temperature within the range of approximately 27–32 °C is considered optimal for *L. vannamei* because it promotes efficient metabolism, digestion, and growth while maintaining stable microbial activity in pond ecosystems (Ponce-Palafox *et al*., 1997; Li *et al*., 2007). Temperature also regulates the rate of biochemical and microbial processes, including organic matter decomposition and oxygen consumption (Bett and Vinatea, 2009; González *et al*., 2010; Vinatea *et al*., 2011). Consequently, relatively stable thermal conditions can help maintain balanced oxygen demand and prevent abrupt shifts in pond biogeochemistry (Ray *et al*., 2010; Vinatea *et al*., 2010; Wada *et al*., 2016; Iber and Kasan, 2021; Kumar *et al*., 2023).

Salinity dynamics in the ponds were influenced by temporal environmental factors such as evaporation, rainfall, and water management practices. Nevertheless, the salinity range recorded in this study (15–30 g L^{-1}) remained well within the tolerance range of L. vannamei, which is recognized as a euryhaline species capable of adapting to broad salinity conditions. Salinity stability is important because osmotic stress can affect shrimp metabolism, energy allocation, and immune responses. In addition, salinity influences microbial community composition and nutrient transformation processes within pond ecosystems, thereby indirectly affecting shrimp health and pond productivity (Li *et al*., 2007; Zeng *et al*., 2024; Wang *et al*., 2025).

Dissolved oxygen concentrations remained within acceptable levels for shrimp culture and showed relatively uniform distribution among ponds. Adequate oxygen availability is essential for shrimp respiration and aerobic microbial processes involved in organic matter degradation and nutrient cycling (Hargreaves, 1998; Avnimelech, 1999; Vinatea *et al*., 2010; Vinatea *et al*., 2011). In intensive shrimp ponds, increasing biomass and feed input often lead to higher organic loading, which can elevate microbial oxygen demand and potentially reduce DO concentrations (Avnimelech, 1999; Ariadi *et al*., 2025; Cao *et al*., 2025). Effective aeration and water circulation therefore play a critical role in maintaining oxygen availability and preventing the accumulation of reduced metabolites that may negatively affect shrimp performance (Takarina *et al*., 2020; Ariadi *et al*., 2025).

Importantly, these water quality parameters should not be considered independently because they are closely interconnected through the ecological processes occurring within the pond ecosystem. For example,

temperature influences microbial metabolism and oxygen consumption, which in turn affects DO availability and CO_2 production (Marcantel *et al*., 2025; Wang *et al*., 2026). These processes subsequently regulate pH dynamics through carbonate equilibrium reactions. Similarly, salinity can influence microbial community structure and shrimp osmoregulation, thereby modifying the overall stability of the pond environment. Such interactions highlight the importance of integrated water quality management in shrimp aquaculture sytem (Wang *et al*., 2025).

Furthermore, pond sediment processes may also play a significant role in regulating water quality dynamics. Organic matter accumulation in pond sediments can stimulate microbial respiration and redox reactions that influence oxygen demand, nutrient release, and CO_2 production (Koue, 2024). These processes may indirectly affect pH stability and overall pond productivity. Previous studies have shown that sediment redox conditions and organic matter dynamics are important determinants of shrimp pond health and environmental stability (Wiyoto *et al*., 2016; Lemonnier *et al*., 2017; Wiyoto *et al*., 2017;).

Overall, the relatively balanced interaction among pH, temperature, salinity, and dissolved oxygen observed in this study indicates that the culture ponds maintained a stable environmental condition suitable for shrimp production. Maintaining such stability is essential in intensive aquaculture systems because fluctuations in one parameter may propagate through the pond ecosystem and influence other environmental variables, microbial activity, and shrimp physiological responses.

The cumulative variance explained by the selected principal components (72.27%) indicates that the model captures a substantial proportion of the total variability. In multivariate analysis, higher cumulative variance is generally interpreted as better representation of the data structure, although no universal threshold exists and adequacy depends on the research context (Jolliffe and Cadima, 2016; Hair *et al*., 2019). The acceptable Kaiser–Meyer–Olkin value (0.636) and the highly significant Bartlett's test further confirm that the dataset contained meaningful correlations among variables and was therefore suitable for multivariate dimensional reduction using PCA.

The first principal component, explaining 42.16% of the total variance, likely represents the main productivity gradient within the shrimp pond ecosystem. The strong loadings of dissolved oxygen, feed input, and average body weight suggest that shrimp growth performance is closely linked with oxygen availability and feeding intensity. Adequate dissolved oxygen is critical for shrimp metabolism, feed digestion, and aerobic microbial processes that regulate organic matter decomposition and nutrient cycling in pond systems. In intensive shrimp aquaculture, oxygen availability often becomes one of the primary drivers of production efficiency because it influences both shrimp respiration and microbial activity responsible for maintaining water quality (Anongponyoskun *et al*., 2012; Ramos-Mendieta *et al*., 2025; Wafi *et al*., 2025)

The negative loadings of salinity and survival rate in PC1 suggest that fluctuations in salinity may influence shrimp survival dynamics. Although *L.vannamei* is known as a euryhaline species capable of tolerating a wide range of salinity conditions, abrupt changes in salinity can induce osmotic stress that affects shrimp physiological balance, immune responses, and survival (Yuchao *et al*., 2019; Shen *et al*., 2019; Saputra *et al*., 2025). Salinity fluctuations may also influence microbial community structure and nutrient availability within pond ecosystems, which indirectly affects shrimp health and productivity (Yu *et al*., 2025; Keneally *et al*., 2026).

The second principal component, dominated by temperature and pH, represents a physicochemical environmental gradient. Temperature plays a fundamental role in regulating metabolic activity, enzymatic reactions, and microbial processes in aquaculture systems. Variations in temperature can influence oxygen demand, nutrient transformation, and phytoplankton productivity in shrimp ponds (Yang *et al*., 2019; Boyd *et al*., 2020). The negative loading of pH in this component suggests an interaction between thermal conditions and carbonate equilibrium in the pond water. In productive aquaculture ponds, temperature and pH are closely linked through photosynthesis and respiration processes that regulate CO_2 dynamics in the water column (Mercante *et al*., 2011; Tang *et al*., 2023).

The third principal component, dominated by specific growth rate and temperature, likely reflects shrimp growth dynamics influenced by environmental conditions. Temperature is known to affect shrimp metabolism, feeding activity, and nutrient assimilation efficiency, which ultimately determine growth performance. Previous studies have shown that temperature variations within the optimal range can significantly influence shrimp growth rate and feed conversion efficiency (Tian *et al*., 2004; Tian and Dong, 2006).

The anti-image correlation matrix further supports the validity of the PCA results, as most variables exhibited Measure of Sampling Adequacy values greater than 0.50, indicating their suitability for inclusion in the model. Only temperature showed a relatively lower MSA value, suggesting weaker correlations with the other variables. This result indicates that temperature may act as an independent environmental driver rather than being strongly correlated with other measured parameters. Similar findings have been reported in aquaculture studies where temperature often acts as a fundamental environmental regulator affecting multiple

biological processes but not always showing strong linear correlations with other water quality variables (Steiner *et al*., 2022).

Overall, the PCA results highlight the interconnected nature of environmental variables and production performance in shrimp pond ecosystems. The dominant role of oxygen availability, feeding intensity, and environmental stability suggests that maintaining balanced water quality conditions is essential for sustaining shrimp growth and survival in intensive aquaculture systems. These findings reinforce the importance of integrated water quality management in shrimp ponds, where multiple environmental parameters interact to regulate biological processes and determine overall production performance.

Conclusion

Water quality conditions in the super-intensive *L. vannamei* culture system remained within suitable ranges throughout the culture period, with pH and salinity showing temporal variation while temperature and dissolved oxygen remained relatively stable. Multivariate analysis revealed significant interactions among water quality parameters and shrimp production indicators, with three principal components explaining most of the variability in the dataset and representing the dominant environmental gradients influencing shrimp performance. These findings highlight the importance of maintaining stable water quality conditions and demonstrate that multivariate approaches can support more effective environmental monitoring and management in super-intensive shrimp aquaculture systems.

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