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Original Article

Growth of milkfish (*Chanos chanos*) under stocking density gradients: Implications for efficiency and environmental stability in aquaculture

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Abstract: Aquaculture is a rapidly growing food production sector, and milkfish (*Chanos chanos*) is a key species in tropical aquaculture due to its high economic value and broad environmental tolerance. However, identifying an optimal stocking density remains a critical challenge, as excessive fish biomass can disrupt the pond's ecological balance and reduce production efficiency. This study evaluated the effects of different stocking densities on milkfish growth performance, survival, feed efficiency, and environmental conditions in pond aquaculture systems. A 60-day experiment was conducted in a semi-intensive brackishwater pond using a completely randomized design with three stocking densities (10, 20, and 30 individuals m^{-2}), each with three replicates. Growth, survival rate, and feed conversion ratio (FCR) were recorded, while water quality parameters—including temperature, pH, dissolved oxygen, salinity, transparency, and sediment redox potential—were monitored weekly. The results showed that stocking density significantly affected fish performance. The lowest density (10 individuals m^{-2}) produced the highest growth (7.83 cm in length and 14.73 g in weight gain), survival (100%), and feed efficiency (FCR 0.68). Increasing density reduced growth and survival while increasing FCR. Higher densities were also associated with lower DO, salinity, transparency, and sediment redox potential, although temperature and pH remained relatively stable. Correlation and regression analyses indicated that DO and water transparency were the main environmental factors influencing milkfish growth, survival, and feed efficiency. These findings highlight the importance of maintaining moderate stocking densities to balance productivity and environmental stability in milkfish pond aquaculture.

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Introduction

Aquaculture is a rapidly growing food production sector that helps meet global demand for aquatic protein while reducing pressure on capture fisheries. In tropical aquaculture, milkfish (*Chanos chanos*) is widely cultured in Southeast Asia for its economic value and adaptability, particularly in pond systems (Verdegem et al., 2023). Its productivity is strongly influenced by management practices, particularly stocking density (Sambu et al., 2024), which affects resource use, environmental carrying capacity, growth, survival, feed efficiency, and production yield (Li et al., 2021).

In pond aquaculture, stocking density is a key factor because ponds function as semi-closed ecosystems. Increasing biomass can alter pond biogeochemistry through nutrient loading, organic matter accumulation, and metabolic waste, affecting dissolved oxygen, pH, water transparency, and sediment redox conditions (Xu et al., 2025). Excessive density may reduce growth and system stability (Chapra et al., 2021), while low density lowers production efficiency; therefore, determining an optimal stocking density is essential for sustainable milkfish culture (Awal et al., 2025).

Previous studies on milkfish culture have examined feeding, fertilization, polyculture, and pond productivity management. However, most focus on single production indicators, with limited attention to interactions between stocking density, fish

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performance, and pond environmental dynamics (Alimorin et al., 2025). Higher densities can increase feed competition, stress, nutrient loading, and metabolic waste, potentially reducing growth and water quality (Meacock and Mitri, 2025). In addition, organic matter accumulation from feed residues and excretion may alter sediment redox conditions, affecting nutrient cycling, microbial processes, and fish responses (Corzo et al., 2018; Seo and Park, 2023; Lai et al., 2025).

Despite widespread milkfish farming, studies that integrate biological performance and environmental responses across stocking-density gradients remain limited, leaving the ecological threshold for pond stability unclear (Alimorin, 2025). Therefore, this study evaluates survival rate, growth, and feed conversion ratio together with water quality parameters—temperature, pH, dissolved oxygen, salinity, transparency, and sediment redox potential—to assess the effects of stocking density on production efficiency and ecosystem stability.

Materials and Methods

Study site and experimental design: The experiment was conducted from September to November 2025 in a 2000 m² brackishwater pond representing a semi-intensive milkfish system (Fig. 1). Experimental units were created using 1×1 m tarpaulin enclosures. A completely randomized design with three stocking densities-low (A), medium (B), and high (C), i.e., 10, 20, and 30 individuals m^{-2}, and three replicates (nine units) was applied. Juvenile milkfish with uniform size were stocked after 24 h acclimation and cultured for 60 days. Fish were fed commercial pellets (28-30% crude protein) twice daily with rations adjusted to biomass. Growth performance and water quality were monitored during the experiment (Al-Zahrani et al., 2024).

Fish growth performance

Absolute length growth: Fish length was measured using a digital caliper with an accuracy of 0.01 cm. Measurements were taken at the beginning and end of the experiment to assess changes in fish length over the culture period. Absolute length growth was calculated using the equation (Surbakti et al., 2022) of $L = L_t - L_o$, where L = absolute length growth (cm), L_0 = initial fish length (cm), and L_t = final fish length (cm).

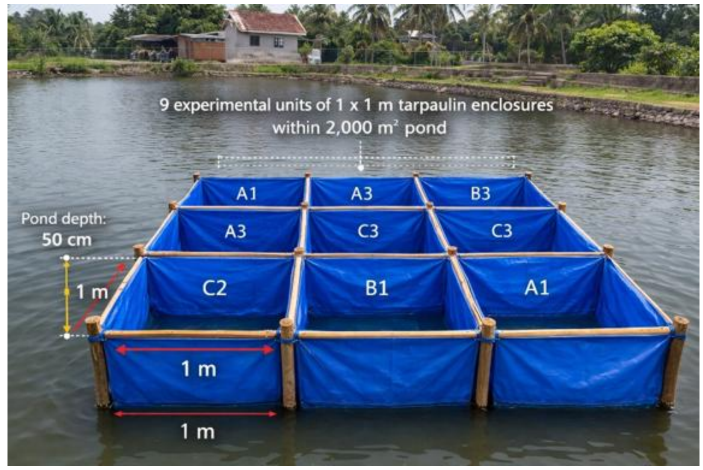

Figure 1. Experimental setup showing nine 1×1 m tarpaulin enclosures arranged in a 3×3 layout within a 2,000 m² milkfish pond used for stocking density treatments.

Absolute weight growth**:** Fish weight was measured using a digital analytical balance with an accuracy of 0.01 g. Measurements were taken at the beginning and end of the experiment to assess changes in fish body weight over the culture period. Absolute weight growth was calculated using the equation (Septiana et al., 2022) of $W = W_t - W_o$, where W = absolute weight growth (g), W_0 = initial fish weight (g), and W_t = final fish weight (g).

Survival rate **(SR):** The percentage of fish that survived during the experimental period. Fish mortality was recorded daily in each experimental unit to calculate the number of surviving individuals at the end of the culture period. Survival rate was calculated using the equation (Muarif et al., 2021) of $SR = N_t/N_o \times 100$, where SR = survival rate (%), N_0 = number of fish stocked at the beginning of the experiment (individuals), and N_t = number of fish remaining at the end of the experiment (individuals).

Feed conversion ratio **(FCR):** FCR is used to evaluate feed utilization efficiency during the culture period. The FCR value represents the amount of feed required to produce a unit of biomass gain. It was calculated using the equation (Muarif et al., 2021) of $FCR = F/W_t - W_o$, where FCR = feed conversion

Table 1. Absolute growth performance of milkfish cultured under different stocking densities

Parameter	Stocking density	N	Mean±SD	F-value	*P*-value
Absolute length (cm)	10	3	7.83±0.12[a]	196.33	<0.001
	20	3	6.83±0.12[b]		
	30	3	5.97±0.12[c]		
Absolute weight (g)	10	3	14.73±0.25[a]	279.81	<0.001
	20	3	11.97±0.31[b]		
	30	3	9.80±0.20[c]		

Note: Values are expressed as mean±standard deviation (n = 3). Different superscript letters within the same row indicate significant differences among treatments at $P<0.05$ based on one-way ANOVA. Stocking density significantly affected absolute length growth (F = 196.33; $P<0.001$) and absolute weight growth (F = 279.81; $P<0.001$).

Table 2. Survival rate (%) of milkfish cultured under different stocking densities.

Parameter	Stocking density (individuals m^{-2})	N	Mean±SD (%)	F-value	*P*-value
	10	3	100.00±0.00[a]	58.90	<0.001
Survival Rate (%)	20	3	93.33±1.53[b]		
	30	3	91.00±1.00[b]		

Note: Values are expressed as mean±standard deviation (n = 3). Different superscript letters within the same column indicate significant differences among treatments at $P<0.05$ based on one-way ANOVA (F = 58.90; $P<0.001$) followed by a post hoc multiple comparison test.

ratio, F = total feed supplied during the experimental period (g), and $W_t - W_0$ = total biomass gains during the culture period (g).

Water quality monitoring: Water quality was monitored weekly to assess environmental conditions affecting fish growth. Samples were collected at a depth of 20-30 cm after instrument calibration. Parameters measured included temperature, dissolved oxygen (DO), pH, salinity, oxidation–reduction potential, and water transparency using standard field instruments. Measurements were conducted at 09:00, 13:00, and 15:00 WIB to account for diurnal variation. Data were summarized as the mean ± standard deviation for each unit prior to statistical analysis (Novianti et al., 2023).

Statistical analysis: All data were analyzed using ANOVA to determine the effects of stocking density on fish growth and water quality. Significant differences ($P<0.05$) were further tested using Tukey's multiple range test (Sukmawantara et al., 2021). Pearson correlation and simple linear regression were used to examine relationships between water quality variables and fish performance indicators. Analyses were conducted using Minitab (version 22.4), while graphs and calculations were prepared in Microsoft Excel (Kodama et al., 2021).

Results

Fish growth performance: Milkfish growth differed significantly among stocking densities (Table 1; Fig. 2). The highest growth occurred at 10 individuals m^{-2}, with absolute length and weight gains of 7.83±0.12 cm and 14.73±0.25 g. Growth decreased at 20 individuals m^{-2} (6.83±0.12 cm; 11.97±0.31 g) and was lowest at 30 individuals m^{-2} (5.97±0.12 cm; 9.80±0.20 g). The results showed significant effects of stocking density on both length (F = 196.33; $P<0.001$) and weight growth (F = 279.81; $P<0.001$), with significant differences among treatments.

Survival rate (%): Based on the results, stocking density significantly affected milkfish survival (F = 58.90; $P<0.001$). The highest survival occurred at 10 individuals m^{-2} (100.00±0.00%), significantly higher than at 20 individuals m^{-2} (93.33±1.53%) and 30 individuals m^{-2} (91.00±1.00%) (Table 2; Fig. 3). No significant difference was found between the two higher densities, indicating that increased stocking density may reduce survival due to greater

Table 3. Feed conversion ratio (FCR) of milkfish cultured under different stocking densities.

Parameter	Stocking Density (individuals m⁻²)	N	Mean±SD	F-value	*P*-value
Feed Conversion Ratio (FCR)	10	3	0.68±0.01[a]	1746.32	<0.001
	20	3	1.53±0.04[b]		
	30	3	2.33±0.05[c]		

Note: Values are expressed as mean±standard deviation (n = 3). Different superscript letters within the same column indicate significant differences among treatments at $P<0.05$ based on one-way ANOVA. Stocking density had a significant effect on FCR ($F = 1746.32$; $P<0.001$).

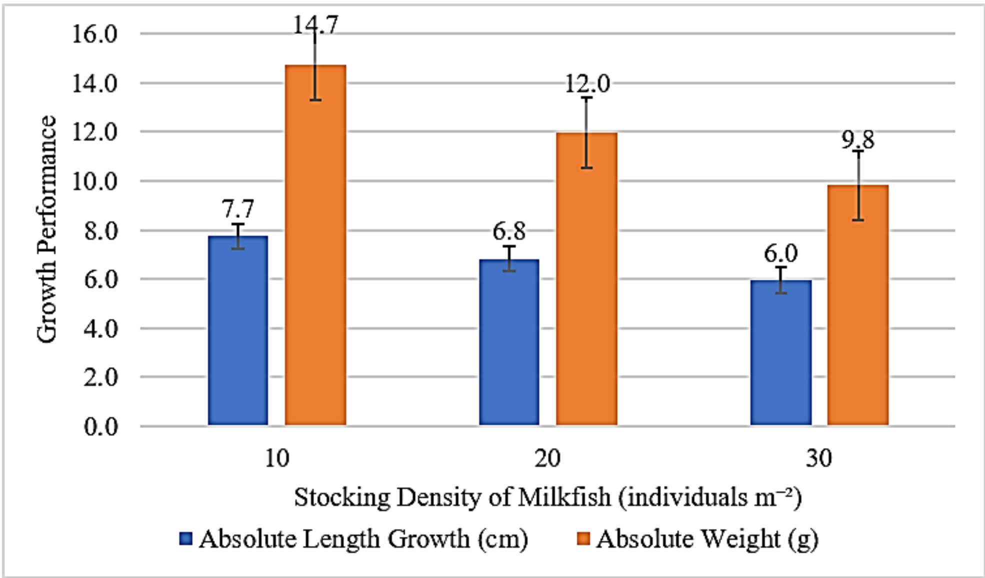

Figure 2. Survival rate (%) of milkfish at different stocking densities (10, 20, and 30 individuals m⁻²). Values are presented as mean±SD (n = 3). Error bars represent standard deviation.

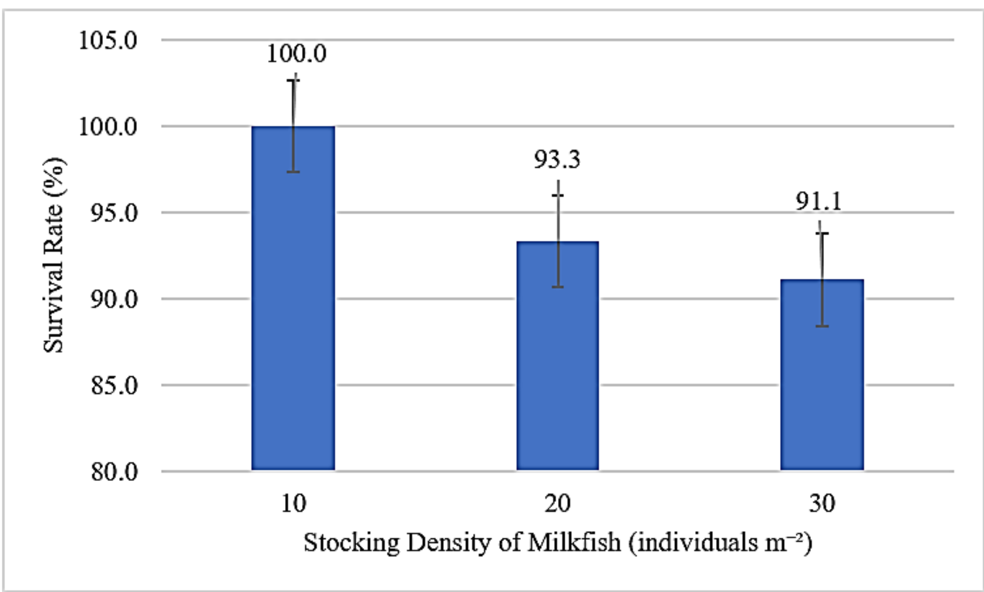

Figure 3. Feed conversion ratio (FCR) of milkfish at different stocking densities (10, 20, and 30 individuals m⁻²). Values are presented as mean ± SD (n = 3). Error bars represent standard deviation.

competition for space and resources.

Feed conversion ratio (FCR): Milkfish FCR differed significantly among stocking densities (Table 3; Fig. 4). The lowest FCR occurred at 10 individuals m⁻²

Table 4. Range of water quality parameters observed in milkfish ponds under different stocking density treatments.

Treatment	Temperature	pH	DO	Salinity	Water transparency	Soil Redox potential
A	28.8-32.1	6.72-7.84	2.4-4.8	5-12	32-58	-25-(-210)
B	29.1-32.6	6.65-7.76	1.9-3.9	5-11	28-51	-40-(-265)
C	29.4-33.0	6.58-7.68	1.4-3.1	4-10	24-46	-55-(-318)

Note: Treatment A = 10 individuals, Treatment B = 20 individuals, and Treatment C = 30 individuals. Values are presented as the observed range during the culture period. Water quality parameters include temperature (°C), pH, dissolved oxygen (DO, mg L^{-1}), salinity (g L^{-1}), water transparency (cm), and sediment redox potential (mV).

Table 5. Water quality parameters in milkfish ponds under different stocking densities based on ANOVA and post hoc analysis.

Parameter	Stocking Density (individuals m^{-2})	N	Mean±SD	F-value	*P*-value
Temperature (°C)	10	3	30.67±0.55[a]	4.59	0.062
	20	3	31.27±0.57[a]		
	30	3	31.97±0.45[a]		
pH	10	3	7.24±0.13[a]	4.80	0.057
	20	3	7.12±0.09[a]		
	30	3	7.00±0.05[a]		
Dissolved Oxygen (mg L^{-1})	10	3	4.17±0.35[a]	34.59	<0.001
	20	3	3.23±0.25[b]		
	30	3	2.30±0.20[c]		
Salinity (g L^{-1})	10	3	9.0±1.0[a]	7.00	0.027
	20	3	8.0±1.0[ab]		
	30	3	6.0±1.0[b]		
Water Transparency (cm)	10	3	51.7±3.5[a]	27.71	<0.001
	20	3	42.3±2.5[b]		
	30	3	35.0±2.0[c]		
Soil Redox Potential (mV)	10	3	−98±20[a]	64.26	<0.001
	20	3	−160±10[b]		
	30	3	−243±15[c]		

Note: Values are mean±SD (n = 3). Different superscript letters indicate significant differences at $P<0.05$ (one-way ANOVA with post hoc test). Stocking density significantly affected dissolved oxygen (F = 34.59; $P<0.001$), salinity (F = 7.00; $P=0.027$), water transparency (F = 27.71; $P<0.001$), and soil redox potential (F = 64.26; $P<0.001$), but not temperature (F = 4.59; $P=0.062$) or pH (F = 4.80; $P=0.057$).

(0.68±0.01), indicating the most efficient use of feed, while higher values were recorded at 20 individuals m^{-2} (1.53±0.04) and 30 individuals m^{-2} (2.33±0.05). The findings revealed a highly significant effect of stocking density on FCR (F = 1746.32; $P<0.001$), with significant differences among all treatments.

Water quality: Water quality varied across stocking densities (Tables 4, 5). Temperature (F = 4.59; $P=0.062$) and pH (F = 4.80; $P=0.057$) were not significantly affected. However, DO decreased from 4.17±0.35 mg L^{-1} at 10 individuals m^{-2} to 2.30±0.20 mg L^{-1} at 30 individuals m^{-2} (F = 34.59; $P<0.001$). Salinity declined from 9.0±1.0 to 6.0±1.0 g L^{-1} (F = 7.00; $P=0.027$), while water transparency decreased from 51.7±3.5 to 35.0±2.0 cm (F = 27.71; $P<0.001$). Sediment redox potential also became more negative from −98±20 to −243±15 mV (F = 64.26; $P<0.001$), indicating significant differences among treatments.

Regression and correlation between water quality and milkfish performance: Pearson correlation showed that DO had the strongest relationships with milkfish performance, positively correlated with length growth (r = 0.92), weight growth (r = 0.95), and survival (r = 0.89), and negatively with FCR (r = −0.94) (Table 6). Water transparency and soil redox potential also showed strong positive correlations with growth and survival, and negative correlations with FCR, whereas temperature and pH showed weaker correlations. Multiple regression indicated that DO and transparency were the main predictors of

Table 6. Pearson correlation coefficients between water quality parameters and milkfish performance indicators.

Parameter	**Length Growth**	**Weight Growth**	**Survival Rate**	**FCR**
Temperature	0.41	0.39	0.36	-0.40
pH	0.52	0.55	0.48	-0.50
Dissolved Oxygen	**0.92**	**0.95**	**0.89**	**-0.94**
Salinity	0.68	0.72	0.70	-0.71
Transparency	**0.88**	**0.91**	**0.86**	**-0.90**
Soil Redox	0.83	0.86	0.80	-0.88

Note: Values represent Pearson correlation coefficients (r) between water quality parameters and milkfish performance (length growth, weight growth, survival rate, and FCR). Positive values indicate direct relationships, while negative values indicate inverse relationships.

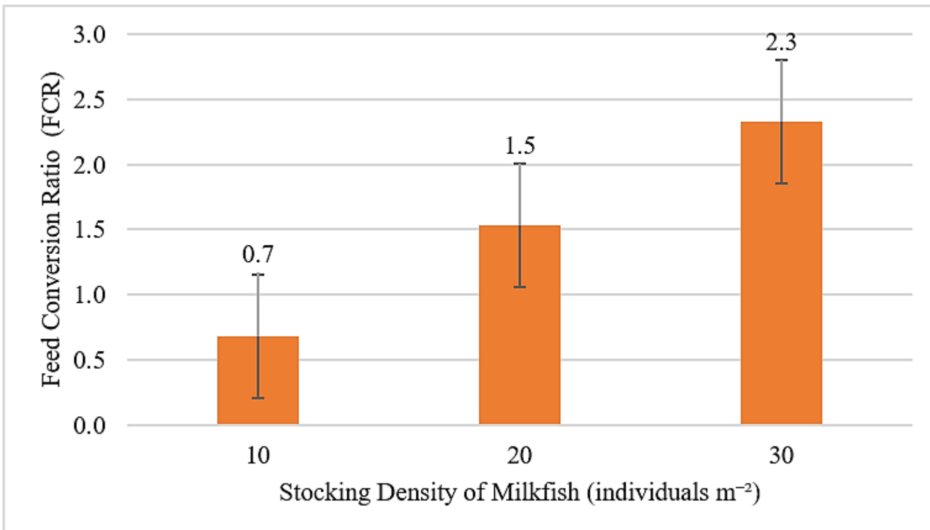

Figure 4. Feed conversion ratio (FCR) of milkfish at different stocking densities (10, 20, and 30 individuals m^{-2}). Values are presented as mean±SD (n = 3). Error bars represent standard deviation.

performance (Table 7). Models included Length = 1.82+1.41(DO)+0.06(Transparency) (R^2 = 0.87), Weight = 2.15+2.38(DO)+0.11(Transparency) (R^2 = 0.91), Survival = 62.5+5.74(DO)+0.28(Transparency) (R^2 = 0.86), and FCR = 3.21–0.52(DO)–0.03 (Transparency) (R^2 = 0.89). Both predictors were significant (P<0.05).

Discussions

The present study demonstrates that stocking density is critical to milkfish growth performance, with significantly higher absolute length and weight gains observed at the lowest density (10 individuals m^{-2}). The progressive decline in growth at higher densities indicates that increased fish biomass intensifies competition for essential resources, including feed, dissolved oxygen, and available space, within the culture environment. Under lower stocking conditions, fish likely experienced reduced behavioral interference and more efficient access to feed, allowing a greater proportion of consumed energy to be allocated toward somatic growth rather than maintenance or stress responses (Warsa et al., 2025). Several environmental mechanisms observed in this study further explain the density-dependent growth pattern. Higher stocking densities were associated with reduced DO, lower water transparency, and increasingly negative sediment redox potential, all of which can indirectly constrain fish growth.

Dissolved oxygen is a primary factor regulating metabolic efficiency in fish; adequate oxygen availability supports aerobic respiration and energy production required for tissue development. Conversely, reduced oxygen levels can limit metabolic performance and suppress growth rates (Abisha et al., 2024). Similarly, declining water

Table 7. Multiple regression models describing the relationships between water quality parameters and milkfish performance indicators.

Response variable	Regression model	Predictor	Coefficient (β)	*P*-value	R^2
Absolute Length Growth (cm)	Length = 1.82+1.41(DO) + 0.06(Transparency)	DO (mg L^{-1})	1.41	<0.01	0.87
		Transparency (cm)	0.06	<0.05	
Absolute Weight Growth (g)	Weight = 2.15+2.38(DO) + 0.11(Transparency)	DO (mg L^{-1})	2.38	<0.01	0.91
		Transparency (cm)	0.11	<0.05	
Survival Rate (%)	Survival = 62.5+5.74(DO) + 0.28(Transparency)	DO (mg L^{-1})	6.82	<0.01	0.86
		Transparency (cm)	0.28	<0.05	
Feed Conversion Ratio (FCR)	FCR = 3.21−0.52(DO) − 0.03(Transparency)	DO (mg L^{-1})	−0.52	<0.01	0.89
		Transparency (cm)	−0.03	<0.05	

Note: Values represent regression coefficients (β) for the effects of dissolved oxygen (DO) and water transparency on milkfish growth, survival, and feed conversion ratio (FCR). The coefficient of determination (R^2) indicates the proportion of variance explained by the model; $P<0.05$ indicates statistical significance.

transparency at higher densities likely reflects increased organic loading and phytoplankton or suspended particles, which may reduce the primary productivity balance and deteriorate pond conditions. A more negative sediment redox potential also indicates intensified organic matter accumulation and oxygen depletion in pond sediments, conditions that can release reduced compounds and further degrade water quality (Sumagaysay and San, 2003).

The strong relationships identified between DO, water transparency, and fish performance in the current study highlight their central role in mediating the effects of stocking density on growth. These parameters collectively reflect the ecological balance of the pond system and the environment's capacity to support fish biomass (Ali and Mishra, 2022). Therefore, the reduced growth observed at 20 and 30 individuals m^{-2} likely results from a combination of physiological stress and environmental deterioration associated with higher fish densities. A notable contribution of this research is the integration of growth performance with key water quality indicators and predictive regression models to identify the environmental drivers of density-dependent growth in milkfish culture systems. By demonstrating that dissolved oxygen and water transparency jointly explain a substantial proportion of variation in growth performance, this study provides a mechanistic framework for understanding how stocking density influences productivity in pond-based milkfish aquaculture (Ji et al., 2025). These findings help refine stocking strategies that balance production intensity with environmental carrying capacity, thereby supporting more sustainable and efficient milkfish farming practices.

The survival rate of milkfish in this study was strongly influenced by stocking density, with the highest survival observed at 10 individuals m^{-2} and a noticeable decline at higher densities. This pattern indicates that lower stocking densities provide a more favorable culture environment that minimizes physiological stress and improves fish's ability to maintain normal metabolic and behavioral functions (Abisha et al., 2024). At higher densities, the increasing biomass in the pond likely intensifies competition for critical resources such as dissolved oxygen, feed availability, and living space, thereby elevating stress levels and increasing the risk of mortality. Although the survival rates at 20 and 30 individuals m^{-2} remained relatively high, the significant reduction relative to the lowest density suggests that the carrying capacity of the culture system approaches its ecological limit as fish density increases (Sambu et al., 2024).

Environmental mechanisms identified in this study help explain the density-dependent survival pattern. Higher stocking densities were associated with reduced dissolved oxygen concentrations and lower water transparency, conditions that can compromise fish physiological performance. DO plays a central role in maintaining respiratory efficiency and supporting essential metabolic processes; therefore, lower oxygen availability can reduce fish tolerance to environmental stress and increase susceptibility to mortality (Jacquier et al., 2021). Similarly, declining water transparency often reflects increased organic matter and suspended particles in the pond, which can alter primary productivity and contribute to unstable water quality. The observed shift toward more negative sediment redox potential at higher densities further indicates greater organic accumulation and oxygen depletion in pond sediments, which may promote the release of reduced compounds that deteriorate overall water quality (Garcia et al., 2019). The strong relationships between water quality parameters and fish performance suggest that DO and water transparency function as key environmental regulators of both growth and survival in milkfish culture systems. This integrated approach represents an important contribution of the present study, as it links stocking density not only to biological performance but also to underlying environmental dynamics within the pond ecosystem (Herawati and Rostini, 2022). By demonstrating that survival declines as ecological conditions deteriorate under higher densities, it highlights the importance of aligning stocking strategies with the environmental carrying capacity of the culture system to sustain both productivity and fish health in milkfish aquaculture (Abdul et al., 2022).

The significant increase in feed conversion ratio with rising stocking density indicates that feed utilization efficiency in milkfish culture is strongly influenced by population density within the pond system. The lowest FCR recorded at 10 individuals m^{-2} suggests that fish maintained at lower densities converted feed into biomass more efficiently, whereas higher densities resulted in substantially poorer feed conversion. This pattern reflects the increasing competition for feed and space as biomass accumulates, which can lead to uneven feed distribution, reduced feeding opportunities for some individuals, and greater energy expenditure associated with competitive interactions. Under such conditions, a larger proportion of consumed energy is diverted toward maintenance metabolism and stress responses rather than growth, ultimately reducing feed efficiency (Li et al., 2021). Environmental dynamics observed in this study further explain the density-related decline in feed utilization efficiency. Increasing stocking density was associated with lower dissolved oxygen concentrations, reduced water transparency, and more negative sediment redox potential, all of which can impair feeding activity and digestive efficiency (Alimorin, 2025). Dissolved oxygen is particularly critical for supporting metabolic processes involved in nutrient assimilation and energy production; insufficient oxygen availability can suppress appetite and reduce feed conversion efficiency (Kim et al., 2023).

Reduced water transparency may also indicate higher levels of suspended organic matter and phytoplankton, which can disrupt the pond's ecological balance and affect natural food availability. Meanwhile, increasingly negative sediment redox potential indicates intensified organic accumulation and oxygen depletion in pond sediments, conditions that may deteriorate water quality and indirectly affect feeding behavior (Arfiati, 2021). The integration of growth, feed efficiency, and environmental parameters in this study provides a clearer understanding of how stocking density regulates production performance in milkfish aquaculture. The strong relationships identified between dissolved oxygen, water transparency, and feed conversion emphasize that feed efficiency is not solely determined by feeding management but is also closely linked to environmental carrying capacity (Widyastuti and Setiadi, 2021). Thus, this research demonstrates that stocking density influences feed utilization through interacting ecological mechanisms within the pond system, highlighting the importance of maintaining optimal density levels to achieve both efficient feed use and sustainable milkfish production.

Water quality dynamics in the present study clearly reflect the ecological consequences of increasing stocking density in milkfish pond systems. Although temperature and pH did not differ significantly among treatments, their relatively stable ranges suggest that these parameters were primarily regulated by external environmental conditions such as climatic factors and natural buffering processes within the pond ecosystem rather than by fish biomass. In contrast, several key parameters-including dissolved oxygen, salinity, water transparency, and sediment redox potential-showed significant density-dependent changes, indicating that the increasing biomass directly influenced the internal ecological balance of the culture system.

The progressive decline in dissolved oxygen with increasing stocking density is consistent with the higher metabolic oxygen demand associated with greater fish biomass and intensified microbial decomposition of organic matter originating from feed residues and fish excretion (Yu et al., 2026). As stocking density increases, the combined oxygen consumption from fish respiration and microbial activity can exceed the pond's natural oxygen replenishment capacity, resulting in reduced dissolved oxygen concentrations. Similarly, the reduction in water transparency observed at higher densities likely reflects increased suspended organic particles, phytoplankton biomass, and detritus generated by uneaten feed and metabolic waste (Abisha et al., 2024). Elevated nutrient loading under higher densities can stimulate plankton growth and increase turbidity, thereby decreasing light penetration and altering the ecological structure of the pond environment (Patang, 2023).

Changes in sediment redox potential further support intensified organic accumulation on the pond bottom. The increasingly negative redox values observed at higher stocking densities indicate increasingly reduced sediment conditions, which occur when oxygen availability in the sediment becomes limited by the decomposition of organic matter. Under such conditions, anaerobic microbial processes dominate, potentially producing reduced compounds that can diffuse into the water column and further affect water quality stability (Adámek and Maršálek, 2013). Meanwhile, the slight decrease in salinity across treatments may be associated with increased freshwater inputs or dilution effects within the pond system, although this parameter remained within a range suitable for milkfish culture. Taken together, these results demonstrate that stocking density not only affects fish production performance but also regulates key environmental processes within the pond ecosystem (Ranasinghe et al., 2024). This study provides a more integrated understanding of how biomass loading influences the ecological balance of ponds. This integrated perspective highlights that optimal stocking density should be determined not only by production targets but also by the environmental carrying capacity of the culture system to maintain stable water quality conditions.

Regression and correlation between water quality and milkfish performance: The correlation and regression analyses provide clear evidence that variations in water quality play a fundamental role in regulating milkfish production performance in pond culture systems. Among all measured parameters, dissolved oxygen was the most influential environmental variable, showing very strong positive correlations with growth and survival and a strong negative relationship with feed conversion ratio. This pattern highlights the central physiological role of oxygen in supporting aerobic metabolism, nutrient assimilation, and energy allocation for somatic growth. Adequate oxygen availability allows fish to efficiently convert feed into biomass, whereas oxygen limitation can suppress feeding activity, reduce metabolic efficiency, and ultimately impair growth and survival (Ali et al., 2022). The regression models further confirm this mechanism, demonstrating that dissolved oxygen substantially explains variation in both growth and feed efficiency across treatments. Water transparency also showed strong relationships with fish performance, indicating that the optical and ecological conditions of the pond water column are closely linked to production outcomes (Lu et al., 2022).

Higher transparency generally reflects lower concentrations of suspended organic matter and a more balanced phytoplankton community, which can stabilize primary productivity and improve overall pond ecological conditions. In contrast, reduced transparency at higher stocking densities likely reflects increased organic loading from feed residues and fish excretion, leading to elevated turbidity and potential deterioration of the aquatic environment. Such conditions may indirectly affect feeding behavior, oxygen dynamics, and the overall energy balance of cultured fish (Abisha et al., 2024). Sediment redox potential showed similarly strong associations with milkfish growth and survival, suggesting that pond-bottom conditions also play a critical role in shaping water quality and production performance. More negative redox values indicate increasingly reduced sediment environments, typically caused by the accumulation and microbial decomposition of organic matter (Sambu et al., 2024). Under such conditions, oxygen depletion in the sediment can promote anaerobic processes that release reduced compounds into the water column, potentially destabilizing pond ecological conditions and affecting fish health. Meanwhile, salinity showed moderate correlations with fish performance, reflecting the importance of maintaining suitable osmotic conditions for milkfish physiology, although its influence was less pronounced than that of oxygen and transparency (Sinkko et al., 2019).

A key contribution of this study is the integration of correlation and regression analyses to identify the primary environmental drivers of milkfish production performance. The high explanatory power of the regression models (R^2 values ranging from 0.86 to 0.91) indicates that a substantial proportion of the variability in growth, survival, and feed efficiency is attributable to dissolved oxygen and water transparency. This finding highlights the ecological linkage between water quality dynamics and production outcomes, providing a quantitative framework for understanding how environmental carrying capacity constrains stocking density in pond aquaculture systems (Sumagaysay and San, 2003). By identifying these key environmental predictors, the present study offers a more mechanistic basis for optimizing stocking strategies and improving the sustainability of milkfish farming.

Conclusion

This study demonstrates that stocking density is a key management factor influencing both biological performance and environmental stability in milkfish (*Chanos chanos*) pond aquaculture. Lower stocking density (10 individuals m^{-2}) resulted in the best production outcomes, including higher growth, survival rate, and feed utilization efficiency, while higher densities significantly reduced these performance indicators. The decline in fish performance at increased densities was closely associated with changes in pond environmental conditions, particularly reductions in dissolved oxygen, water transparency, salinity, and sediment redox potential. In contrast, temperature and pH remained relatively stable and were not significantly affected by stocking density. Correlation and regression analyses further revealed that dissolved oxygen and water transparency were the most influential environmental predictors of milkfish performance, explaining a substantial proportion of variation in growth, survival, and feed conversion ratio. These findings indicate that stocking density not only regulates fish biomass but also affects the ecological balance of pond systems by influencing key water quality processes. Overall, maintaining moderate stocking densities that sustain adequate oxygen availability and stable water transparency is essential to optimize production efficiency while preserving environmental stability. The integrated evaluation of fish performance and water quality parameters presented in this study provides a practical framework for determining environmentally sustainable stocking strategies in pond-based milkfish aquaculture.

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