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Temporal water-quality variability and its implications for environmental management of sand lobster aquaculture

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ABSTRACT

BACKGROUND AND OBJECTIVES: Sustainable management of sand lobster aquaculture is often limited by monitoring approaches that summarize environmental conditions using long-term averages, obscuring short-term extremes and spatial variation. The study objectives were to characterize spatial and temporal variations in water quality within a floating net cage aquaculture system, identify their underlying physical drivers, evaluate whether longitudinal growth is governed more by culture duration, initial size, and stocking density than by environmental exposure alone, and translate these empirical relationships into a transferable environmental monitoring framework.
METHODS: The study collected longitudinal growth and environmental data from floating net cage culture in Indonesia. Monitoring covered temperature, salinity, oxygen concentration, potential of hydrogen, and nutrient concentrations across three water depths and multiple sampling times. Non-parametric statistical tests were employed to evaluate depth-dependent variations in dissolved oxygen, while correlation and regression analysis assessed the relationships between wind speed, water temperature, and dissolved oxygen levels. Multivariate statistical ordination summarized dominant environmental gradients, and mixed-effects statistical models, compared through an information-theoretic model selection approach, captured longitudinal growth.
FINDINGS: Dissolved oxygen concentration differed significantly among depths (test statistic 29.27, probability below 0.001), declining by close to a fifth from the surface to three and ten meters. Monthly wind speed closely tracked the concurrent decline in temperature closely (correlation coefficient -0.988, probability below 0.002) but exhibited no statistically significant association with dissolved oxygen, consistent with a wind-driven transition observed during this production cycle. Culture duration, initial size class, and stocking density together explained total length best, with an additive model carrying more than seventy percent of the statistical weight among six candidate models. Growth rate exhibited its strongest association with low-oxygen exposure, followed by temperature and potential of hydrogen condition, an interpretation that warrants caution given the limited independent exposure intervals available.
CONCLUSION: Successful sand lobster aquaculture requires an adaptive environmental monitoring architecture that accounts for depth-related oxygen stratification and wind-driven seasonal variability, alongside coordinated management of culture duration, initial seed size, and stocking density. The analytical framework of integrated site assessment and management for lobster can be adapted to other marine aquaculture systems through the inclusion of species-specific biological indicators and management variables.

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54	7	2

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INTRODUCTION

Marine aquaculture has become one of the fastest-growing food-production sectors worldwide, playing an increasingly important role in food security, coastal livelihoods, and blue-economy development as capture fisheries face pressure from overexploitation and environmental degradation (Norman *et al*., 2019; Mair *et al*., 2023). Among high-value marine commodities, the scalloped or sand spiny lobster, *Panulirus homarus*, has drawn substantial interest owing to its exceptional market value and promising potential for aquaculture expansion (Zhou *et al*., 2026; Minjoyo *et al*., 2024). Because physiological performance, molting, and survival are heavily governed by environmental parameters such as temperature, salinity, dissolved oxygen (DO), and potential of hydrogen (pH) (Vidya and Joseph, 2012; Minjoyo *et al*., 2024); site suitability for lobster aquaculture must be evaluated as a dynamic production challenge rather than a static environmental classification. Conventional aquaculture site-selection approaches commonly assess physicochemical, spatial, and infrastructural variables against species-specific suitability criteria using Geographic Information System (GIS), remote sensing, and multi-criteria decision analysis (Porporato *et al*., 2020; Jayanthi *et al*., 2022). However, these approaches primarily establish environmental or spatial suitability without guaranteeing that a site will achieve favorable biological performance under a specific combination of stocking, feeding, and culture duration, as growth and survival can vary substantially even where ambient environmental conditions are broadly favorable (Kulmiye and Mavuti, 2005; Adiyana *et al*., 2020; Minjoyo *et al*., 2024). An additional drawback of conventional suitability assessments is their reliance on long-term environmental averages, which can mask critical short-term fluctuations and extreme events of ecological significance. Recent integrated water-quality monitoring research has similarly emphasized that conventional manual and stationary monitoring can provide inadequate spatial and temporal resolution, whereas stratified and multi-location monitoring can better resolve depth-dependent and short-term water-quality variation (Wahyono *et al.,* 2026). High-frequency observations from aquaculture sites have shown that DO can vary markedly among seasons and even among cages within the same site (Jeong *et al*., 2024; Breitburg *et al*., 2015), and marine organisms may experience environmental extremes that differ substantially from long-term means (Kroeker *et al*., 2023). This pattern is not limited to temperate systems: a seasonal water-quality assessment of a floating-net-cage site in Pegametan Bay, Bali found DO ranging from 2.6–9.1 milligrams per liter (mg/L) in the dry season versus 3.4–7.7 mg/L in the wet season (Ariadji *et al*., 2024), a spread a single seasonal average would not reveal. Consequently, in longitudinal studies, environmental conditions ought to be characterized as temporally aligned exposure variables rather than relied upon as isolated single-point or averaged measurements. Discrete-time monitoring at fixed depths and sampling occasions, rather than continuous logging, is a common and accepted practice in aquaculture water-quality monitoring (Jeong *et al*., 2024), and depth-resolved profiling of the water column is similarly an established approach for characterizing the vertical DOD structure relevant to cage aquaculture (Oldham *et al.,* 2018). Aside from temporal averaging, environmental parameters often exhibit systematic fluctuations driven by seasonal-scale physical processes. Tidal currents and rainfall-driven discharge are also recognized as important physical drivers of stratification and oxygen dynamics in tropical coastal systems (Lee *et al.,* 2020), though not directly measured here, consistent with prior studies evaluating a single physical driver as a tractable indicator of broader forcing (Soeyanto *et al.,* 2026). In semi-enclosed tropical coastal waters, seasonal wind forcing is a primary control

on circulation, stratification, and oxygen dynamics; a recent study of Jakarta Bay, Indonesia demonstrated a significant wind–transport correlation ($r > 0.5$, $p < 0.01$) supporting an early-warning framework for hypoxia at bay scale (Soeyanto *et al*., 2026). Vertical DO heterogeneity within cage culture systems is well established for pelagic finfish, with larger and deeper enclosures consistently exhibiting lower oxygen saturation than shallower counterparts (Oldham *et al*., 2018). For *P. homarus* specifically, depth-related effects have already been reported in Indonesia: a comparison of sub-mersible cages at 6 m and 8 m in Kepulauan Seribu found no depth effect on immune indicators (Wahjuningrum *et al*., 2022), while a grow-out trial in Pangandaran reported markedly better feed conversion at 5 m than at shallower depths, attributed to greater thermal and oxygen stability (Sarkar *et al*., 2026). However, the intra-water column oxygen-exposure gradient and its direct relationship with with growth performance rather than immune or feed-conversion endpoints, have not yet been quantified for this species. Accordingly, this study establishes the lobster integrated site assessment and management (LISAM) architecture, as a protocol for aligning depth-resolved, physically indexed environmental monitoring with species-specific biological responses to support adaptive management at operating aquaculture facilities. Conceptually, this architecture is built on the premise that environmentally favorable sites do not automatically ensure optimal production, and that sustainable aquaculture planning must synthesize environmental traits, biological performance, operational constraints, and managerial decisions (Jayanthi *et al*., 2022; Mair *et al*., 2023; Zhou *et al*., 2026; Shahat *et al.,* 2026). While demonstrated at a single site in Batam, Indonesia, the analytical architecture underlying LISAM is not specific to this location or species: it is the sequence of depth-resolved environmental characterization, physical-driver identification, and growth-linked biomanagement modelling those transfers, not the specific numerical thresholds reported here. Applying LISAM elsewhere means substituting these with the target system's own values and biomanagement variables. Accordingly, this study aims to characterize the temporal and depth-dependent environmental variability associated with sand lobster aquaculture; isolate its underlying physical drivers, including wind-driven seasonal transitions; evaluate whether longitudinal growth is better predicted by culture duration alone or by multifactorial models incorporating initial size class and stocking density; assess if temporally synchronized environmental exposure metrics improve biological performance predictions after accounting for biomanagement effects and translate these supported relationships into a transferable environmental-monitoring framework for the adaptive management of *P. homarus* aquaculture under tropical coastal conditions. The aim of the study is to apply LISAM architecture, aligning depth-resolved oceanographic monitoring with biomanagement and longitudinal biological performance in sand lobster (*Panulirus homarus*) aquaculture. This study was carried out in Batam Islands, Indonesia. Environmental and biological data were collected in 2025 and 2026.

MATERIALS AND METHODS

Study site and culture system

The study was conducted in the coastal waters of Setokok Island, Batam City, Riau Islands Province, Indonesia, within the Singapore Strait, one of Indonesia's principal centers for sand lobster (*Panulirus homarus*) floating-net-cage (FNC) culture. Data was obtained from representative FNC aquaculture locations, namely marine aquaculture development (BPBL) Batam (Fig. 1), which differ in hydrodynamic characteristics, water exchange, coastal exposure, and site-specific physical conditions while maintaining comparable culture systems. This spatial variability among otherwise comparable sites provides a natural framework for evaluating the

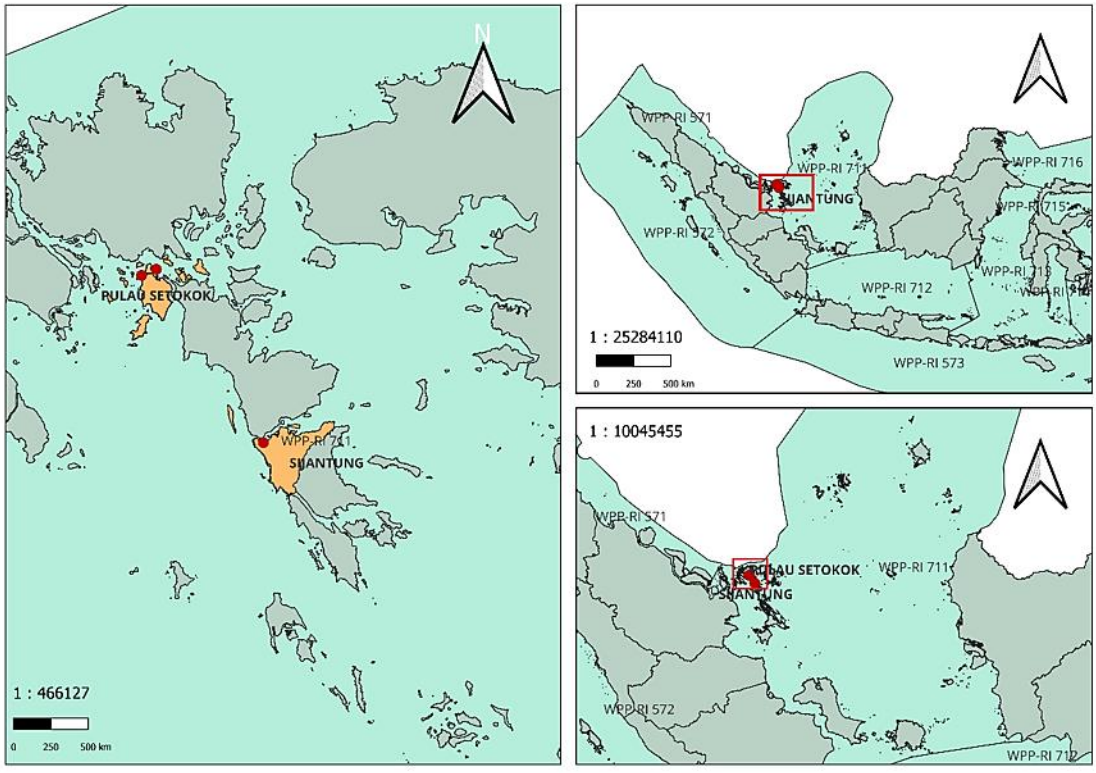

Fig. 1: Geographical location of the study area in Batam Island, Indonesia

complex interplay among environmental conditions, farm management practices, and biological performance (Radhakrishnan *et al*. 2019; FAO, 2024). Field observations were carried out over a single five-month production cycle using a longitudinal monitoring design, wherein oceanographic parameters were measured concurrently with biological sampling at each site to capture both spatial (among-site) and temporal (within-cycle) environmental variability.

Environmental monitoring

Environmental observations collected representative stationary points were retained for quality control but excluded from biological exposure calculations. Culture-site measurements of temperature, DO, pH, and salinity were summarized for each biological growth interval rather than matched to a single sampling date. Exposure metrics encompassed the mean, standard deviation, minimum, and maximum for each variable, alongside stress-oriented indices such as the percentage of observations falling below a defined DO threshold, using Eqs. 1 and 2 (Jeong *et al*., 2024):

$$DO_{<5} = 100(n_{DO<5}/n_{DO}) \quad (1)$$

$$DO_{<4} = 100(n_{DO<4}/n_{DO}) \quad (2)$$

For each growth interval, this proportion aggregated all discrete depth-and-time observations gathered across the interval's monitoring campaigns, encompassing three depths × five diel sampling occasions per campaign, rather than relying on single-point measurement or a simple mean. Nevertheless, exposure itself was characterized by discrete sampling events rather than continuously logged or duration-weighted data. Environmental monitoring events were given equal weight when deriving interval summaries.

Biological growth data

Longitudinal growth and environmental data from sand lobster (*Panulirus homarus*) cultured in FNC were analyzed using a cage-based repeated-measures framework. Due to the logistical constraints of tracking individual lobsters across multiple sampling intervals, statistical analyses treated the rearing cage as the primary experimental unit. The study was conducted at a single site (BPBL Batam) using six floating net cages, representing all combinations of three initial size classes (small, medium, large) and two stocking densities (50 and 75 individuals per cage), with one cage assigned to each combination. Rather than employing a randomized design, treatment allocations were fixed, and replicate cages per treatment combination were omitted. Instead, individual cages underwent repeated sampling across five successive monthly intervals throughout the five-month culture period, thereby providing the robust longitudinal growth datasets examined herein. For each cage and sampling period, mean body weight and total length (TL) were calculated, following cage-based growth assessments commonly used in *P. homarus* culture studies, using Eq. 3 (Prayanti *et al*., 2026):

$$AG = Y_{t_2} - Y_{t_1} \quad (3)$$

Biological performance between two sampling times (t_1, t_2) was quantified as absolute growth (AG). The relative growth (RG) is applied using Eq. 4 (Sun and Wang, 2024):

$$RG = 100\left(Y_{t_2} - Y_{t_1}\right)/Y_{t_1} \quad (4)$$

The specific growth rate (SGR) for body weight is applied using Eq. 5 (Sun and Wang, 2024):

$$SGR = 100\left[\ln\left(W_{t_2}\right) - \ln\left(W_{t_1}\right)\right]/(t_2 - t_1) \quad (5)$$

It is expressed as percent (%) per day. Length growth rate (LGR) was calculated, using Eq. 6 (Kristiana *et al*., 2020):

$$LGR = \left(L_{t_2} - L_{t_1}\right)/(t_2 - t_1) \quad (6)$$

Total length was selected as the primary response metric for the biomanagement models owing to its near-linear trajectory throughout the culture phase. Conversely, SGR was applied in the environmental models to normalize growth performance across monitoring intervals of varying lengths (20–29 days). The continuous predictors were standardized where required, using Eq. 7 (Ignatz *et al*., 2021):

$$z = (x - \bar{x})/s_x \quad (7)$$

Depth-stratified DO analysis

Water quality was monitored at a single representative station within each site across three depths, with sampling conducted five times per diel cycle over five monthly campaigns (September–January), generating a total of 75 distinct depth-resolved observations (3 depths × 5 diel occasions × 5 campaigns). Classifying DO relative to a biological threshold, rather than mean concentration alone, is informative given that DO in tropical floating-net-cage systems is known to vary substantially, with a comparable Indonesian FNC site reporting a range of 2.6–9.1 mg/L across seasons (Ariadji *et al.,* 2024) and in other tropical crustacean aquaculture systems (>37% in shrimp ponds (Tho *et al.,* 2011). Values below this threshold may indicate that the conditions at the site are potentially unsuitable for *Panulirus homorus* culture. To assess water-column stratification of DO, measurements taken at the three sampled depths with 0, 3, and 10 meters (m) were evaluated using the Kruskal–Wallis's test whenever the assumptions of normality or homogeneity of variance were violated. Where the global test indicated a significant difference among depths, pairwise post-hoc comparisons (Tukey's HSD or Dunn's test, respectively) were performed to identify which depth strata differed from one another. This analysis evaluated the influence of cage depth on

DO, to establish whether depth- dependent oxygen stratification constituted a consistent pattern rather than a negligible phenomenon.

Physical correlates of environmental variability

To investigate the physical drivers of observed temporal variability in water quality, monthly wind speeds were analyzed against monthly mean temperature and DO using Pearson correlation, or Spearman's rank correlation for non-normal data, and simple linear regression, reporting regression coefficients, coefficients of determination (R^2), and 95% confidence intervals. This analysis aimed to determine whether seasonal wind forcing could account for the collinearity between culture duration and environmental predictors noted in the Results.

Multivariate environmental characterization

Principal Component Analysis (PCA) was employed to characterize covariance structures among the standardized environmental parameters. Prior to component extraction, sampling adequacy and variable intercorrelation were assessed using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's Test of Sphericity. Components exhibiting eigenvalues greater than one were retained in accordance with the Kaiser criterion, and Varimax rotation was applied to ease interpretation of the resulting gradients, using Eq. 8 (Jolliffe and Cadima, 2016):

$$PC_k = a_{1k}Z_1 + a_{2k}Z_2 + \cdots + a_{pk}Z_p \quad (8)$$

Where: a_{jk}denotes the loading of standardized variable; $Z_j$on component k.

Biomanagement growth models (LMM)

Longitudinal biological responses were analyzed using Linear Mixed-Effects Models (LMMs). The general model, using Eq. 9 (Augie *et al.*, 2025):

$$Y_{it} = X_{it}\beta + u_i + \varepsilon_{it} \quad (9)$$

Where: $Y_{it}$is the response for cage $i$at time t, βrepresents fixed effects, $u_i \sim N(0, \sigma^2_{cage})$is the cage-specific random intercept, and $\varepsilon_{it}$is the residual error. Temporal dependence within cages was represented using a continuous first-order autoregressive structure, using Eq. 10 (Hamel *et al.*, 2012):

$$\mathrm{Cor}(\varepsilon_{it}, \varepsilon_{is}) = \phi^{|t-s|} \quad (10)$$

A cage-specific random intercept, combined with this within-cage, was considered appropriate, repeated monthly measurements within each of six cages, with no individual-lobster tracking and no additional site to model. This architecture permits cages to vary systematically in their baseline growth while accounting for temporal autocorrelation, wherein measurements separated by shorter intervals within the same cage exhibit stronger correlation than those spaced further apart. Six biologically defined candidate models were subsequently evaluated using Eqs. 11 to 16 (Zuur *et al.*, 2009):

$$M_0: Y \sim 1; \quad (11)$$

$$M_T: Y \sim Time; \quad (12)$$

$$M_{TS}: Y \sim Time \times Size; \quad (13)$$

$$M_A: Y \sim Time + Size + Density; \quad (14)$$

$$M_{TD}: Y \sim Time \times Density + Size; \quad (15)$$

$$M_I: Y \sim Time \times Size + Time \times Density + Size \times Density \quad (16)$$

Environmental–growth association models

Environmental effects on interval-specific SGR were examined as extensions of the biomanagement baseline, using Eq. 17 (Sun and Wang, 2024):

$$SGR \sim Time + Size + Density \quad (17)$$

To prevent over-parameterization given the restricted number of independent environmental exposure periods, standardized temperature, mean DO, low-DO exposure, pH, or salinity were incorporated into models individually. Interactions between environmental variables and biomanagement factors (e.g., density × DO) were not tested, despite evidence from other crustacean species that such interactions may influence biological responses (Kumar *et al.,* 2024). Due to the limited availability of only four independent environmental exposure intervals, the inclusion of additional interaction terms was deemed unfeasible.

Model selection

Candidate models were fitted using maximum likelihood (ML) and ranked using the Akaike information criterion corrected for small sample size small sample (AICc) (Hurvich and Tsai, 1993; Zhu *et al.,* 2009):

$$AIC_c = AIC + \frac{2K(K+1)}{n-K-1} \quad (18)$$

Where: K is the number of estimated parameters and; n is the number of observations. Relative support was quantified, using Eq. 19 (Hodson *et al*., 2024):

$$\Delta_i = AIC_{c,i} - AIC_{c,\min} \quad (19)$$

and Akaike weight, using Eq. 20 (Hodson *et al*., 2024):

$$w_i = \exp(-0.5\Delta_i) / \sum_r \exp(-0.5\Delta_r) \quad (20)$$

Parameter estimation and inference relied exclusively on the single best-supported model rather than incorporating model-averaged estimates across candidate models. The best-supported model was subsequently refitted using restricted maximum likelihood (REML) for final parameter estimation, confidence intervals, variance components, and residual diagnostics. Because multiple enclosures shared identical environmental conditions within each growth interval, the environmental models were interpreted as exploratory.

RESULTS AND DISCUSSION

Temporal variability of water quality

Environmental conditions were characterized using quality-controlled in situ observations collected across the culture period. Across all depths and cage, water temperature averaged 26.235 ± 0.884 °C with range of 27.53–30.20 degree Celcius (°C), salinity averaged 32.447 ± 0.110 Parts per thousand (ppt) (range 32.29–32.62 ppt), DO averaged 5.502 ± 0.350 mg/L (range 5.00–5.95 mg/L), and pH averaged 8.238 ± 0.190 (range 7.97–8.61) (Table 1). Temperature and salinity are established physicochemical drivers of physiological and production performance in spiny lobster aquaculture (Balkhair *et al*., 2012), whereas DO limits aerobic metabolism acts as a primary determinant of stress and growth in cultured crustaceans (Zheng *et al*., 2021; Brennan *et al*., 2016). Nitrate (1.643 ± 0.444 mg/L), phosphate (0.0093 ± 0.0110 mg/L), and chlorophyll-a (2.447 ± 1.052 µg/L) provide additional characterization of the nutrient and productivity regime. Wind direction and wind speed (3.685 ± 2.386 m/s) further describe the physical setting and atmospheric forcing of the study area. Temperature, dissolved oxygen, phosphate, chlorophyll-a, and wind direction departed significantly from normality (all $p < 0.05$) (Table 1), motivating the use of a non-parametric approach for depth comparison. These baseline patterns also provide important context for distinguishing natural environmental variability from depth-related changes in subsequent analyses. Within the LISAM framework, this baseline characterization anchors the initial analytical layer by defining the temporal envelope of water-quality conditions and establishing a foundation for subsequent depth-resolved, wind-driven, multivariate, and ecological analyses.

Table 1: Descriptive statistics of environmental variables

Variable	Unit	Mean	Standard deviation (SD)	Min	Max	Shapiro–Wilk p
pH	–	8.238	0.190	7.97	8.61	0.240
Temperature	°C	29.235	0.884	27.53	30.20	0.020*
Salinity	ppt	32.447	0.110	32.29	32.62	0.378
DO	mg/L	5.502	0.350	5.00	5.95	0.044*
Nitrate	mg/L	1.643	0.444	0.91	2.34	0.496
Phosphate	mg/L	0.0093	0.0110	0.00	0.03	0.004*
Chlorophyll-a	µg L^{-1}	2.447	1.052	1.13	4.02	0.035*
Wind direction	°	-8.92	127.07	-178.54	177.59	0.041*
Wind speed	m/s	3.685	2.238	0.95	7.45	0.527

* $p < .05$, departs from normality

Depth-stratified oxygen distribution

Because DO is not necessarily homogeneous throughout the water column occupied by a floating cage, DO was compared across three sampled depths (0, 3, and 10 m; n = 75 depth-resolved observations). Mean DO was 6.032 ± 0.586 mg/L at the surface, 4.947 ± 0.550 mg/L at 3 m, and 4.940 ± 0.754 mg/L at 10 m. Because Shapiro–Wilk tests indicated non-normal distributions within each depth stratum, the Kruskal–Wallis test was applied as the primary comparison: the global difference among depths was highly significant ($H = 28.61$, $p < 0.001$). Levene's test confirmed homogeneity of variance across depths ($p = 0.410$). Tukey's HSD post-hoc test revealed that surface DO values differed significantly from those at both 3 m and 10 m (both $p < 0.001$), whereas 3 m and 10 m depths showed no significant difference ($p = 0.999$) (Fig. 2). This pattern demonstrates that lobsters maintained at depths of 3 m or greater encounter DO levels near the lower limit of the 5–7 mg/L range deemed acceptable for floating-net-cage *Panulirus homarus* culture (Syahrir et al., 2024), whereas surface-deployed enclosures remain safely above this critical threshold. These findings quantitatively extend depth-related effects previously reported for *P. homarus* in Indonesia (Wahjuningrum *et al*., 2022; Sarkar *et al*., 2026) and depth-related DO stratification in cage aquaculture more broadly (Oldham *et al*., 2018). Within LISAM framework, this vertical configuration establishes a spatially resolved component of the initial analytical layer, thereby complementing the temporal assessment.

Wind as a correlate of the seasonal transition in environmental variability

Monthly wind speed was strongly and significantly associated with the concurrent decline in water temperature (Pearson $r = -0.988$, $p = 0.002$; temperature = 30.69 - 0.392 × wind speed, $R^2 = 0.975$, 95% CI for the slope [-0.506, -0.277]), but was not significantly associated with DO ($r = -0.810$, $p = 0.096$; $R^2 = 0.656$, 95% CI for the slope [-0.241, 0.034]) (Fig. 3). The strong wind–temperature relationship aligns with wind acting as a physical driver of the seasonal transition in environmental variability, thereby offering a mechanistic explanation for the correlation between culture duration and environmental predictors. This pattern aligns with findings by Soeyanto *et al*. (2026), who demonstrated that seasonal wind forcing governs circulation, stratification, and oxygen dynamics in adjacent Jakarta Bay, thereby suggesting a similar wind–transport relationship to underpin a bay-scale early-warning framework for hypoxia. The present analysis extends this concept to the scale of an individual aquaculture operation and links it to measured biological growth responses rather than to hydrodynamic indicators alone. The lack of a statistically significant wind–DO relationship implies that, unlike temperature, oxygen variability at this site is governed by additional mechanisms, such as biological oxygen demand or

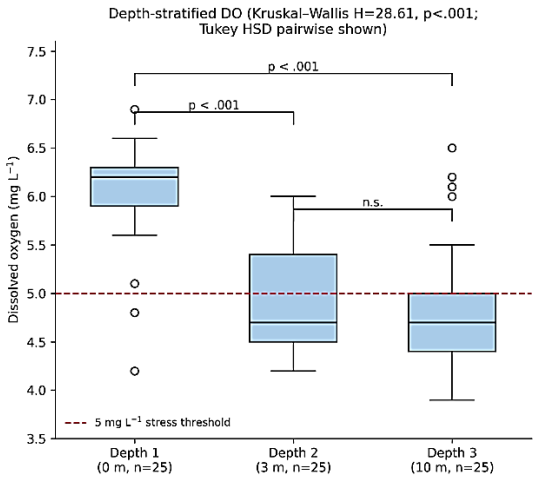

Fig. 2: DO by cage depth (0, 3, 10 m; n = 75). Kruskal–Wallis H = 28.61, p < .001; brackets show Tukey HSD pairwise comparisons

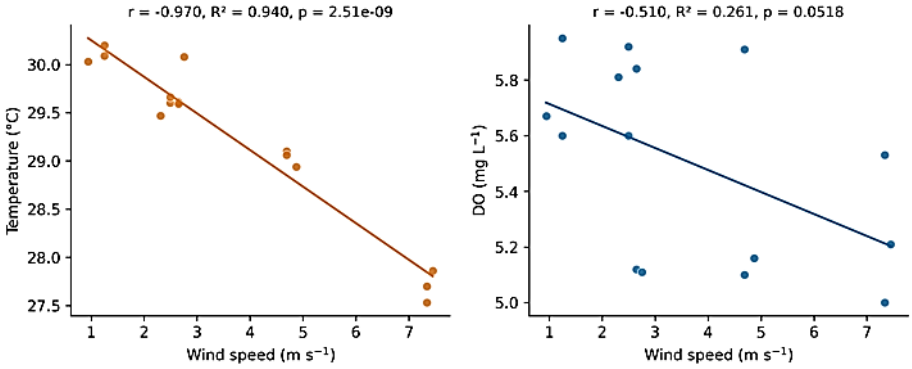

Fig. 3: Monthly wind speed vs. temperature and DO

localized mixing, that wind speed alone does not capture. Within LISAM, wind speed constitutes a low-cost, forecastable physical indicator that can be layered onto the environmental-characterization stage to anticipate the seasonal transition before its biological consequences materialize.

Site characteristics as descriptive context

Site suitability was further characterized using spatial and physical attributes compared across three floating-net-cage (FNC) locations (BPBL Batam, Sijantung, and Taman Laut), to support understanding of how these spatial attributes are interrelated and can be reduced to a small number of interpretable components. This comparative framework complements the single-site environmental and biological monitoring conducted at BPBL Batam, the site selected for cage-based culture in this study, by providing key data on accessibility, proximity to land and marine protected areas (MPA), exposure, bathymetry, and substrate attributes frequently integrated into GIS-based suitability assessments for floating-net-cage lobster aquaculture (Syahrir *et al*., 2024). Accessibility distance ranged from 69.06 to 1,724.51 m (mean 625.06 ± 824.61 m), distance to land ranged from 0 to 140.94 m (mean 53.50 ± 65.09 m), and distance to the nearest MPA ranged from 648.98 to 3,473.03 m (mean 2,162.92 ±

1,232.37 m), indicating considerable variation in spatial accessibility and positioning within the surrounding coastal landscape. Several variables warrant cautious interpretation: the "inside MPA" metric was uniformly zero, denoting that no monitoring sites fall within a protected zone; substrate type was coded categorically on a 1–4 scale, meaning its numerical mean (3.11 ± 0.93) does not represent a physical quantity; and bathymetry exhibited a narrow numerical range (0.9680–0.9878), reflecting a normalized index rather than direct water depth (Mabula *et al*., 2023). To characterize the joint structure among these attributes, PCA was applied. Several methodological limitations must be noted: given the comparison of only three locations, the underlying correlation matrix is necessarily rank-deficient (maximum rank = 2) and several variable pairs exhibit perfect or near-perfect collinearity (e.g., distance to MPA and bathymetry, r = -0.966). The component solution was derived by eigendecomposition of the Pearson correlation matrix. Because only three locations were compared, the matrix rank is mathematically bounded at two, consistent with the reported two-component solution, and is presented here as a low-dimensional descriptive summary of covariation among the three sites rather than a generalizable multivariate structure. Consequently, the resulting components should be interpreted as a descriptive summary of how these attributes covary across the three study locations, rather than as statistically robust or generalizable environmental gradients. Together, two components accounted for 81.46% of the total variance (PC1 = 46.23%, PC2 = 35.23% after Varimax rotation). PC1 was dominated by accessibility distance (0.933), exposure (0.926), and distance to land (0.918); while PC2 was dominated by distance to MPA (-0.973) and bathymetry (0.950); substrate did not load strongly (< 0.50) on either rotated component (Fig. 4). Aligned with the monitoring-architecture principles of LISAM, these site attributes and their multivariate structure serve as a descriptive locational context rather than as fixed-effect predictors within the biological growth models. Formally integrating site-characteristic gradients with growth performance represents a logical next step once future sampling resolves the collinearity.

Multivariate structure of environmental gradients

PCA revealed that the first two components accounted for 84.0% of the total environmental variance. Specifically, the first principal component (PC1) explained 47.8% and was primarily driven by temperature and pH; because DO contributed in the same direction as temperature, PC1 represents a temperature–oxygen versus pH gradient. The second principal component (PC2) explained 36.2% of the variance and was predominantly driven by salinity, which opposed by DO and pH, thereby representing a salinity versus oxygen–pH gradient. The third principal component (PC3) and fourth principal component (PC4) explained only 14.4% and 1.58%, respectively. PCA is frequently employed to condense covariance structures among correlated environmental metrics and to isolate the primary multivariate gradients characterizing complex ecological datasets (Li *et al*., 2017). Condensing multiple correlated environmental metrics into a concise set of interpretable gradients forms the core of LISAM's initial analytical layer. This approach supplies standardized environmental descriptors that can be linked to biological performance without introducing the multicollinearity inherent in incorporating all raw physicochemical variables simultaneously (Zuur *et al*., 2009).

Biomanagement effects on total length growth

Information-theoretic model selection established that the Additive model — incorporating culture time, initial size class, and stocking density entered as additive fixed effects, provided the best-supported explanation for total length variation (AICc = 60.3, Akaike weight = 0.715; Table 2 and Fig. 5. The Time_Density model

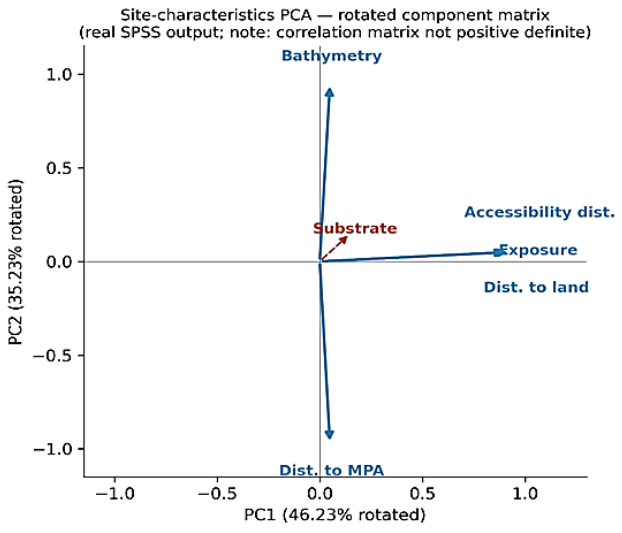

Fig. 4: Site-characteristics PCA

Table 2: AICc-based selection of candidate models for total length growth

Rank	Model	n	K	AICc	ΔAICc	Akaike weight (w_i)	Relative support	Decision
1	Additive	30	8	60.3	0.00	0.715	Strongest	Best-supported model
2	Time density	30	9	62.4	2.10	0.251	Secondary support	Plausible alternative
3	Time size	30	9	66.5	6.17	0.0327	Weak	Considerably less supported
4	Integrated biomanagement	30	13	71.9	11.6	0.00218	Very weak	Little support
5	Time	30	5	105.0	44.8	1.31×10^{-10}	Negligible	Not supported
6	Null	30	4	398.0	337.6–338	3.48×10^{-74}	Negligible	Not supported

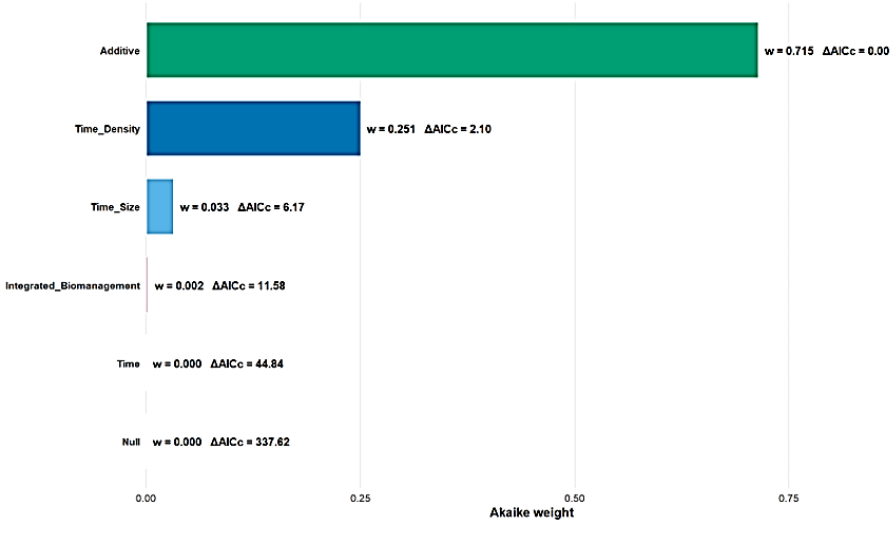

Fig. 5: AICc-based model selection for total length growth of sand lobster (*Panulirus homarus*) seed under different biomanagement hypotheses

received secondary support (AICc = 62.4, weight = 0.251); combined, these two models accounted for approximately 96.6% of cumulative Akaike weight, while the Time_Size interaction, Integrated_Biomanagement, Time-only, and Null models exhibited progressively weaker support. The REML-fitted Additive model confirmed a strong positive effect of culture time (β = 1.260, standard error (SE) = 0.026, p < 0.001); medium-size lobsters were on average 1.280 cm longer than the small-size class (p < 0.001), and large-size lobsters 1.731 cm longer (p < 0.001), after accounting for time and density. Higher stocking density (75 vs. 50 individuals per cage) was associated with a modest, non-significant reduction in length (-0.181 cm, SE = 0.097), consistent with lower-density treatments generally producing better growth in juvenile *P. homarus* (Minjoyo *et al.*, 2024) rather than definitive evidence of a density effect (Fig. 6). The very large ΔAICc values for the Time-only and Null models indicate strong relative support for the Additive structure within this candidate set. Nevertheless, these metrics should be viewed as comparative evidence among the six evaluated models rather than conclusive proof that time, size, and density dictate growth independently of unmeasured variables. Furthermore, the limited support for the more complex Integrated_Biomanagement model indicates that incorporating interaction terms failed to improve model fit sufficiently to penalize the added complexity.

Environmental associations with weight growth

Given that interval-specific environmental exposure was derived from just four independent monitoring intervals across a single ~5-month production cycle, this environmental-growth analysis is treated as exploratory rather than confirmatory; consequently, the reported coefficients and model rankings represent dataset-specific associations rather than generalizable inferential evidence. Building on the biomanagement baseline, environmental variables were evaluated as additional predictors of interval-specific SGR. Among these, the model extending the baseline with low-DO exposure (Bio_DOstress) received the strongest support, followed by temperature and pH; together these three models accounted for approximately 99.5% of cumulative Akaike weight. SGR showed a negative association with culture time (β = -0.767, SE = 0.129), a predictor similarly limited by the four available exposure intervals; relative to the small size class, medium and large lobsters showed lower SGR (β = -0.681, p = 0.017; β = -0.721, p = 0.013), while stocking density showed little association (β = 0.040, p = 0.850). Low-DO exposure showed a positive conditional association with SGR (β = 0.497, SE = 0.129, p < .001). Nevertheless, this estimate derives from only four independent environmental exposure intervals (culture months two through five) in which multiple enclosures shared identical monthly conditions; consequently, the reported p-value should not be construed as indicative of robust statistical certainty. Examined at the interval level, mean SGR declined from 2.87 to 2.50 %/day between the second and third months while mean DO remained unchanged (5.60 mg/L), then rose to 2.75 %/day in the fourth month as mean DO fell to 5.10 mg/L, before both declined together in the fifth month (DO = 5.00 mg/L, SGR = 1.44 %/day). Rather than signaling a genuine dose-dependent trend, this non-monotonic pattern arises from the sparse and uneven parameter combinations available across the four intervals, and it must not be misconstrued as proof that reduced DO enhances lobster growth. To probe this association further, a partial-residual analysis were performed (Fig. 7) to evaluate the relationship between DO and SGR after adjusting for the fitted effects of culture time, size class, and stocking density. The unadjusted bivariate relationship between DO and SGR was positive (r = 0.54, p = 0.007), aligning with the expected biological mechanism whereby higher oxygen availability enhances growth performance.

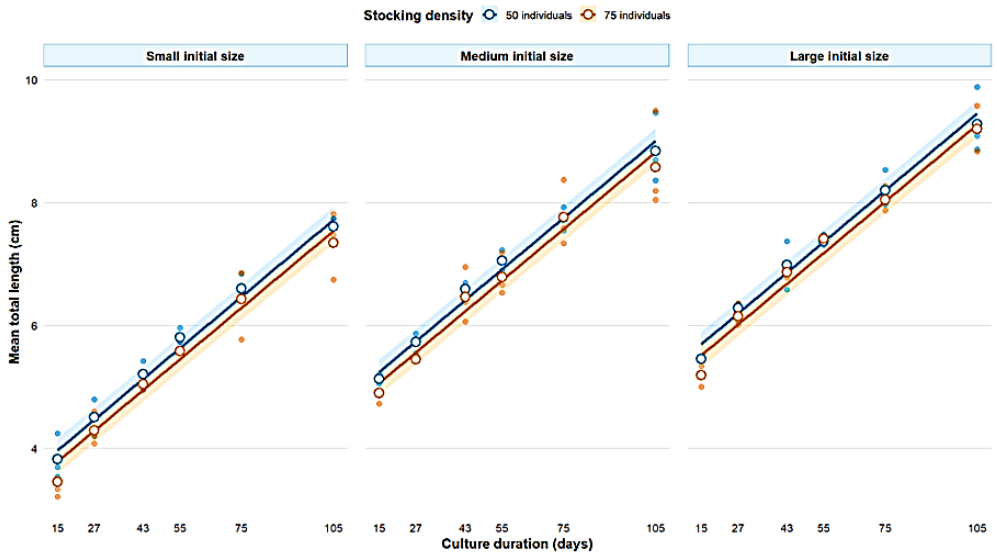

Fig. 6: Observed and model-predicted total length trajectories of sand lobster (*Panulirus homarus*) seed according to initial size class and stocking density

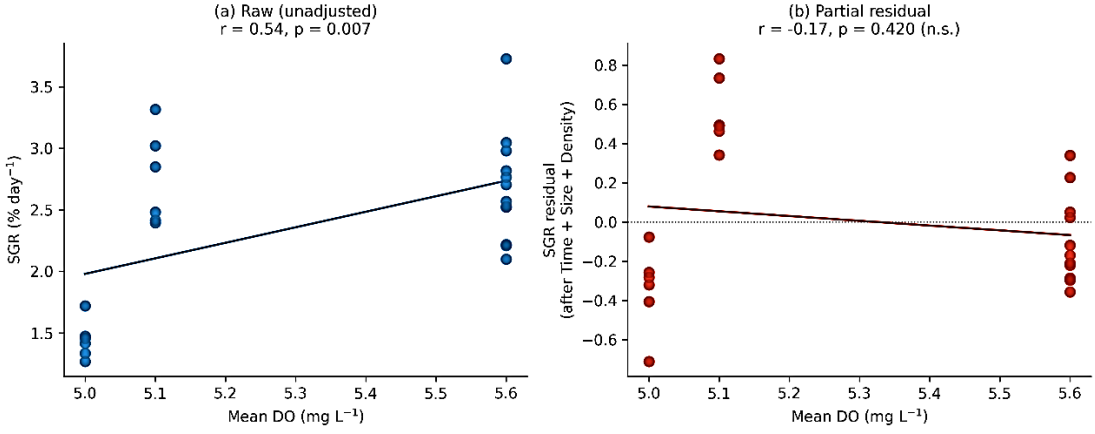

Fig. 7: DO–SGR relationship across 24 cage-interval observations. (a) Raw correlation (r = 0.54, p = 0.007). (b) Partial residual after removing culture time, size class, and stocking density (r = −0.17, p = 0.420, n.s.), indicating the raw association is confounded with the temporal growth trend

This relationship was no longer significant once the shared temporal trend was removed (partial residual r = −0.17, p = 0.420). Furthermore, incorporating DO alongside culture time in the same model also substantially inflated the estimated magnitude of the time effect and triggered a severe rise in multicollinearity (with the condition number surging from 15.8 to 390). This demonstrates that the apparent DO–SGR relationship noted earlier is unstable, arising more parsimoniously from collinearity between DO and culture time than from a genuine, independent influence of oxygen availability on growth. Consequently, this association is not construed as proof that reduced oxygen levels enhance or benefits lobster growth; rather, it is presented strictly as a descriptive trend that merits further examination across additional independent exposure intervals. This association was also interpreted cautiously because culture time was

strongly correlated with temperature (r = -0.947) and pH (r = 0.949), while low-DO exposure was itself correlated with time (r = 0.592) and pH (r = 0.783). This collinearity between culture time and environmental predictors is consistent with, and onsistent with, and physically plausible given, the wind-related seasonal transition, rather than representing an unexplained statistical artefact. Collectively, the biomanagement and environmental evaluations demonstrate that successful sand lobster culture cannot be attributed to management practices or oceanographic conditions in isolation. Culture duration, initial seed size, and stocking density structure the biological growth trajectory, while temporal variability in DO, temperature, and pH provides additional environmental information relevant to culture performance. This represents the third analytical layer of LISAM: identifying which environmental gradients best explain biological performance alongside key biomanagement drivers.

Implications for adaptive environmental management

The biomanagement and environmental-association models identify what matters for sand lobster growth: culture duration, initial size, stocking density, and, more cautiously, DO exposure. The large depth effect on DO (Kruskal–Wallis H = 29.27, $p < 0.001$) means depth is a relevant dimension for environmental monitoring in this system, one that operators should track explicitly rather than assume uniform across the water column. Although depth trends suggest that enclosures positioned closer to the surface would experience higher DO , this study did not evaluate whether surface placement translate to enhanced growth, survival, feed conversion, or welfare. Furthermore, it did it assess how depth influences temperature, hydrodynamics, biofouling, or food availability, variables that covary with depth and could potentially offset any oxygen-related advantage. Repositioning cages toward the surface should therefore be treated as a hypothesis warranting direct experimental testing rather than an operational recommendation. In the interim, monitoring protocols should encompass multiple depth strata; relying on a single surface or mid-column reading risks misrepresenting the actual environmental conditions experienced by lobsters housed deeper within the same enclosure. This matches water-quality guidance for pond and cage aquaculture (Asmah *et al*., 2021), documented crustacean sensitivity to hypoxia (Zheng *et al*., 2021), and known environmental effects on fished lobsters and crabs (Green *et al*., 2014). Within this monitoring framework, routine seasonal variability can be differentiated from potentially critical conditions by comparing new observations against established temporal baseline and predefined biological or environmental trigger levels; can initiate intensified monitoring or proactive management intervention. Wind speed is inexpensive and publicly forecastable through national weather advisories, and the strong wind–temperature relationship (r=-0.988, p=0.0017) turns it into a low-cost indicator for the temperature-related seasonal transition. Operators who monitor these shifts gain valuable lead time to modify feeding, stocking, or harvest schedules before the resulting biological consequences materialize. Consequently, precision-aquaculture research relies on such proxies to anticipate production risks rather than documenting them post-hoc (Kapetsky *et al*., 2013; Falconer *et al*., 2016). However, wind speed showed no significant association with DO (r = -0.810, p = 0.096) in this dataset, so it should not be treated as an early-warning indicator for oxygen risk specifically; oxygen conditions still require direct measurement. Together, the depth and wind results give the biomanagement findings a monitoring logic they lacked before: operators now have grounds for deciding where in the water column, and when in the season, to concentrate monitoring effort. Culture duration, initial seed size, and stocking density govern total length variations, whereas DO, temperature, and pH

provide additional explanatory power regarding weight gain. Integrated statistical assessment of aquaculture water-quality variables can similarly help distinguish relationships among environmental conditions and aquaculture-related responses, supporting the use of multivariable rather than single-parameter assessments (Takarina *et al.,* 2025). Together these results argue against treating site selection and farm management as separate decisions. A physically monitored site will not automatically produce good growth if biomanagement is mismatched to it, and good biomanagement in turn needs a site's environmental variability actively monitored and anticipated, not assumed constant (Giri *et al*., 2023; Radhakrishnan *et al*., 2019). Aquaculture systems behave as coupled social-ecological systems: production outcomes depend on continuous interaction between environmental variability and management decisions, not on either factor alone (Ostrom, 2009; Folke *et al*., 2010). This integrated perspective is consistent with contemporary marine and fisheries strategies that link aquaculture development with environmental sustainability and broader blue-economy objectives (Trenggono *et al.,* 2025). These recommendations rely fundamentally on maintaining the monitoring framework from which they were derived. In this context, adaptive management entails continuously updating operational practices in response to incoming monitoring data, requiring the architecture to be sustained over time rather than deployed merely as a one-time characterization exercise (Costa-Pierce, 2010; Costello *et al*., 2020). To position this contribution more precisely, GIS-based multi-criteria frameworks commonly used for lobster and finfish cage-aquaculture site assessment (Jayanthi *et al*., 2022; Porporato *et al*., 2020; Syahrir *et al*., 2024) are designed to compare candidate locations before operation begins, drawing on static or snapshot environmental and spatial layers to produce a composite suitability score; they do not incorporate depth-resolved temporal monitoring or link their outputs to measured biological performance. In contrast, the LISAM framework is implemented post-site selection. It conceptualizes environmental fluctuations as longitudinal, depth-profiled attributes within an individual operating facility, subsequently connecting them to somatic growth outcomes through the mixed-effects model outlined above. The two approaches are therefore complementary rather than competing: GIS-based multi-criteria assessment remains appropriate for initial site screening, while LISAM addresses the subsequent, and comparatively underdeveloped, problem of managing an operating site once selected. LISAM's novelty sits less in any single statistical technique and more in what it couples together, and at what scale. Separate bodies of research within coastal oceanography and aquaculture provide distinct theoretical and empirical support for depth-related oxygen stratification and wind-driven physical forcing. Linking both physical drivers, at the scale of a single floating-net-cage operation, to measured growth outcomes for a high-value benthic crustacean such as *P. homarus* has not been done before (Zhou *et al*., 2026; Giri *et al*., 2023). Conventional site-selection frameworks (Radiarta *et al*., 2008; Falconer *et al*., 2016; Jayanthi *et al*., 2022; Porporato *et al*., 2020; Syahrir *et al*., 2024) evaluate environmental or spatial suitability largely apart from biomanagement and biological response. LISAM treats environmental characterization, physical-driver identification, biomanagement, and growth modelling as layers of one analytical architecture, producing operational monitoring and management recommendations instead of a static suitability score. The biomanagement models explain why that design matters biologically, without functioning as the central claim. The primary practical outcome is a standardized protocol establishing systematic criteria for selecting monitoring variables, frequencies, and spatial scales. This framework directly responds to contemporary calls for holistic aquaculture

decision-support tools capable of integrating ecological, operational, and adaptive-management facets into a unified workflow (Mair *et al*., 2023; Sampantamit *et al*., 2020). Several parts of this analysis remain preliminary. With only four independent environmental exposure intervals, the environmental-growth analysis (Eq. 17) is formally underpowered for detecting effects independent of culture time; this is demonstrated empirically, not just assumed, by the loss of the DO–SGR signal under partial-residual analysis. Because the cage-based growth assessment utilized a single, non-randomized enclosure per size class–density treatment, cross-combination comparisons warrant cautious interpretation. The depth-stratified DO comparison reflects measurements from a single representative stationary point rather than all six cages, and may not capture cage-to-cage environmental heterogeneity across the site. The original DO–SGR association rests on four independent exposure intervals within a single 5-month production cycle, limiting the ability to separate environmental from temporal effects. This study did not incorporate feeding regime, feed quantity, feed type, feeding frequency, survival/mortality, moulting, disease or health status, shelter availability, handling practices, or other cage-specific management variables, all of which can independently influence growth in *P. homarus* and related palinurid species (Adiyana *et al.,* 2020; Prayanti *et al.,* 2026). Consequently, the documented associations should be viewed as reflecting only the specific set of biomanagement and environmental parameters quantified, rather than an exhaustive account of all growth determinants. The site-characteristics PCA is limited by a non-positive-definite correlation matrix given the current sample size. The wind-speed early-warning idea remains a statistical association, not yet a tested field protocol. Derived likewise from an isolated five-month production cycle, the seasonal and predictive assertions regarding this wind–temperature interaction warrant interpretation as preliminary observations rather than validated, operational early-warning capabilities. More monitoring cycles, full three-site coverage, and an operational trial of the wind indicator would move LISAM toward a fully validated version. LISAM's analytical architecture carries no location-specific parameter. It specifies a type of monitoring (depth-resolved, physically indexed, and growth-linked) not a fixed set of thresholds. Operators can transfer it to other marine aquaculture species and systems (Radhakrishnan *et al*., 2019; Zhou *et al*., 2026) by substituting the relevant environmental variables, depth structure, and biological indicators. This matches calls for aquaculture decision-support frameworks that generalize across species and settings instead of being rebuilt for each case (Kapetsky *et al*., 2013).

CONCLUSION

Successful sand lobster (*Panulirus homarus*) aquaculture in floating net cages requires treating environmental monitoring and biomanagement as one integrated problem across the production cycle. This study characterizes spatial and temporal variations in water quality at an operational aquaculture site and identifies their physical correlates. Furthermore, it quantifies the extent to which growth performance is independently explained by culture duration, initial seed size, and stocking density versus the additional contribution of environmental factors. DO averaged about 6.0 mg/L at the surface and dropped to about 4.9 mg/L at 3 m and 10 m. A Kruskal–Wallis test confirmed this difference ($H = 29.27$, $p < 0.001$), and pairwise comparison showed the surface differed from both deeper strata ($p < 0.001$) while the two deeper strata matched each other. Cages held at 3 m or deeper sit close to the 5 mg/L threshold associated with physiological stress in cultured crustaceans. Monthly wind speed and temperature exhibited a strong inverse seasonal co-variation ($r = -0.988$, $p = 0.002$), whereas wind speed demonstrated no statistically significant association with DO

(r = -0.810, p = 0.096) in this single-site dataset. This coastal system's season transition is a measurable, forecastable driver of the water-quality conditions lobsters experience. Among the evaluated parameters, culture duration, initial seed size, and stocking density collectively provided superior model performance in accounting for total length development. Among six candidate models, an additive model combining these three variables carried the strongest statistical support (Akaike weight = 0.715), well ahead of the next-best model (weight = 0.251). These three variables set the pace of structural growth under the conditions monitored here. SGR followed a different pattern. Low-oxygen exposure carried the strongest environmental signal (β = 0.497, p < 0.001), followed by temperature and pH conditions, even after accounting for time (β = -0.767, p < 0.001), size, and density. Because this relationship is derived from four distinct environmental exposure periods, additional monitoring cycles are required to validate its robustness. Oxygen availability is the physicochemical variable most worth monitoring closely at this class of site. DO concentrations approached the 5 mg/L threshold associated with physiological stress more closely under less favorable cage placement and seasonal timing. Whether relocating aquaculture enclosures closer to the surface—where dissolved oxygen levels remain consistently elevated—translates into enhanced growth, survival, or welfare remains unproven and warrants targeted experimental validation, given that depth simultaneously co-varies with temperature, hydrodynamics, biofouling, and trophic resource availability. Monitor water quality across depth strata, not at a single fixed point. Treat locally forecastable wind conditions as an early indicator of the seasonal transition that precedes oxygen stress, ahead of any signal from DO itself. By integrating species-specific biological indicators and management variables, the analytical framework of LISAM can be readily adapted to other marine aquaculture systems.

AUTHOR CONTRIBUTIONS

I.N.P. Winata conceptualized the study framework and prepared the initial draft of the manuscript. I.M. Radjawane supervised the overall research and provided critical revisions to the manuscript. S. Nurdjaman contributed to research supervision and the literature review, while I.N. Radiarta supported the study through supervision and provided critical comments to strengthen the manuscript. D. Sidik participated in field sampling and data collection, and Deby contributed essential supporting data for the study. S.K. Pratiwi assisted with laboratory analyses. A.A. Utama contributed to data analysis, S. Makmur participated in the interpretation of the results, and Husnah provided critical comments on the manuscript. A. Suman contributed to the development of the conceptual framework and supported the literature review. All authors reviewed and approved the final version of the manuscript prior to publication.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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NEGATIVE AI STATEMENT

The author(s) declared that no AI tools or services were used or highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
Δ_i	AICc difference for candidate model i
ΔAICc	Difference between the AICc of a candidate model and the minimum AICc
β	Fixed-effect regression coefficient
β	Vector of fixed-effect coefficients
ε_{it}	Residual error for cage $i$at time t
σ^2_{cage}	Between-cage random-intercept variance
ϕ	Temporal autocorrelation parameter
°C	Degree Celsius
%/day	Percent per day
µg/L	Microgram per liter
Additive	Model including additive effects of culture time, initial size class, and stocking density
AG	Absolute Growth
AICc	Akaike information criterion corrected for small sample size
a_{jk}	PCA loading of standardized variable $j$on principal component k
ANOVA	Analysis of variance
Bio_DOmean	Biomanagement model extended with mean dissolved oxygen
Bio_DOstress	Biomanagement model extended with low-DO exposure
Bio_pH	Biomanagement model extended with pH
Bio_Salinity	Biomanagement model extended with salinity
Bio_Temperature	Biomanagement model extended with temperature
BioManagement	Baseline model containing culture time, initial size class, and stocking density
BPBL	Marine Aquaculture Development Center (*Balai Perikanan Budidaya Laut*)
cm	Centimeter
DO	Dissolved Oxygen
FNC	Floating Net Cage
GIS	Geographic Information System

Integrated_Biomanagement	Model incorporating culture time, size, density, and their specified pairwise interactions
K	Number of estimated parameters used in AICc calculation
KMO	Kaiser–Meyer–Olkin
LGR	Length Growth Rate
LISAM	Lobster Integrated Site Assessment and Management
LMM	Linear Mixed-Effects Model
m	Meter
m/s	Meter per second
mg/L	Milligrams per liter
ML	Maximum Likelihood
MPA	Marine Protected Area
n	Number of observations
Null	Model containing an intercept only
PC1	First Principal Component
PC2	Second Principal Component
PC3	Third Principal Component
PC4	Fourth Principal Component
PCA	Principal Component Analysis
pH	Measure of acidity–alkalinity based on hydrogen-ion activity
ppt	Parts per thousand
r	Correlation coefficient
REML	Restricted Maximum Likelihood
RG	Relative Growth
SD	Standard Deviation
SE	Standard Error
SGR	Specific Growth Rate
Time	Model including culture time as the explanatory variable
Time_density	Model including culture time, stocking density, their interaction, and initial size class
Time_size	Model including culture time, initial size class, and their interaction
u_i	Cage-specific random intercept
w_i	Akaike weight of candidate model i
X_{it}	Fixed-effect design/predictor vector for cage $i$at time t
Y_{it}	Biological response for cage $i$at observation time t
Z_j	Standardized environmental variable $j$in PCA

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