



Morphometric Responses of the Green Mussel (*Perna viridis*) under Water Quality Gradients in Northern Semarang Coastal Waters

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Abstract



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Although coastal water-quality variability is a major modulator of physiological performance and growth in marine bivalves, the effects of specific parameters on morphometric responses remain poorly constrained. Quantifying associations between environmental gradients and morphometry of green mussel (*Perna viridis*) in the northern coast of Semarang, Indonesia, influenced by differential anthropogenic pressures. A total of 790 individuals were sampled from four sites during September–October 2024, spanning estuarine, port, and aquaculture environments, and in situ measurements of temperature, salinity, pH, dissolved oxygen, transparency, and depth were obtained at two sampling events. We performed nonparametric statistical analyses, such as Spearman's rank correlation and heatmap visualizations) to examine environment–trait associations. Salinity was the dominant predictor, consistently showing a positive correlation with all morphometric traits (the strongest with shell height, $\rho = 0.764$), and indicating a central role in regulating both shell growth and biomineralization. The negative relationships with dissolved oxygen, on the other hand, were moderate ($\rho = -0.462$) and likely reflected hydrodynamic effects rather than a true physiological constraint. Weaker and less consistent associations were observed for other parameters. Of the traits examined, shell height was the most sensitive indicator of environmental variability. Interestingly, mussels from the aquaculture site (Station 4) exhibited larger morphometric traits than wild mussels, indicating that cultivation under more stable conditions can enhance growth performance. These results represent the first quantitative evidence of salinity-triggered morphometric plasticity; they further support *P. viridis* as a suitable bioindicator species for characterizing coastal water quality and classifying aquaculture sites.

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1. Introduction

Coastal areas are vital for biodiversity and fisheries that support human livelihoods. However, anthropogenic activities such as industrial and agricultural practices, port operations, and aquaculture can contaminate marine ecosystems by introducing nutrients, heavy metals, microplastics, and sediments. These inputs modify the physical, chemical, and biological properties of coastal waters and can negatively affect aquatic organisms (Herawati et al., 2021). For instance, rising water temperature can reduce body size in marine species adapted to thermally stable environments (Prakash, 2021).

Macroinvertebrates are widely used as bioindicators of aquatic environments due to their abundance and high

sensitivity to environmental change (Bonacina et al., 2023). Among them, bivalves are considered particularly effective bioindicators because their filter-feeding behavior, long lifespan, and measurable physiological and morphometric responses make them highly responsive to variations in water quality (Vereycken and Aldridge, 2023; Yulianto et al., 2020).

The green mussel (*Perna viridis*) is a sessile bivalve that tolerates environmental fluctuations and attaches to substrates via byssal threads (Inoue et al., 2021). As a filter feeder, it can accumulate dissolved substances from the surrounding water, thereby reflecting the quality of the habitat. Owing to these characteristics, *P. viridis* is widely used in assessments of coastal environmental change and

holds substantial economic importance in the coastal waters of Semarang, with a recorded catch of 961,476 kg and a value of Rp. 6,262,867,000 in 2024 (Semarang Fisheries Office, 2025).

The northern coast of Semarang—encompassing the West and East Banjir Kanal (WBK and EBK), Tanjung Emas Port (TEP), and shellfish aquaculture areas (SAA)—is a highly productive coastal region influenced by intensive human activities. Port operations, industrial effluents, and aquaculture practices are likely to drive spatial and temporal variability in key water-quality parameters, including temperature, salinity, water transparency, and dissolved oxygen (Rahmadi et al., 2021; Tamba et al., 2025; Pangalasan et al., 2025). Such environmental variability is expected to affect green mussel morphometrics as part of the species' physiological responses to local conditions. Accordingly, *Perna viridis* has strong potential as an ecological indicator of water-quality differences across coastal zones.

Understanding morphometric responses is important because variations in water quality, such as temperature, salinity, transparency, pH, dissolved oxygen, and depth, can influence growth, metabolism, and overall physiological condition. As a result, morphometric traits serve as informative proxies for habitat suitability and organismal health. Under deteriorating environmental conditions, green mussels may experience physiological stress, leading to reduced body size and growth performance (Al-Barwani et al., 2016).

Given the ecological and economic importance of green mussels in Semarang Coastal Waters, this study aimed to identify the water-quality parameters most strongly associated with *P. viridis* morphometrics, determine the most responsive morphometric traits, and evaluate which sampling site provides the most favorable conditions for green mussel growth.

2. Material and methods

2.1. Sampling design and data collection

Green mussels (*Perna viridis*) and in situ water-quality data were collected from four sampling stations along the northern coast of Semarang, Central Java, Indonesia, during September and October 2024. All sampling stations are located within the same coastal system along the northern coast of Semarang, representing a relatively confined study area. The distances between stations range from approximately 1.2 to 5.4 km (Figure 1). Despite their proximity, each station was deliberately selected to capture distinct environmental conditions and anthropogenic influences, including estuarine inputs, port activities, and aquaculture areas, thereby representing a clear local environmental gradient. A total of 790 individuals were sampled, comprising 400 specimens during the first sampling period (100 individuals per station) and 390 specimens during the second sampling period (100 individuals per station, except Station 4, where only 90 individuals were collected due to limited natural stock availability).

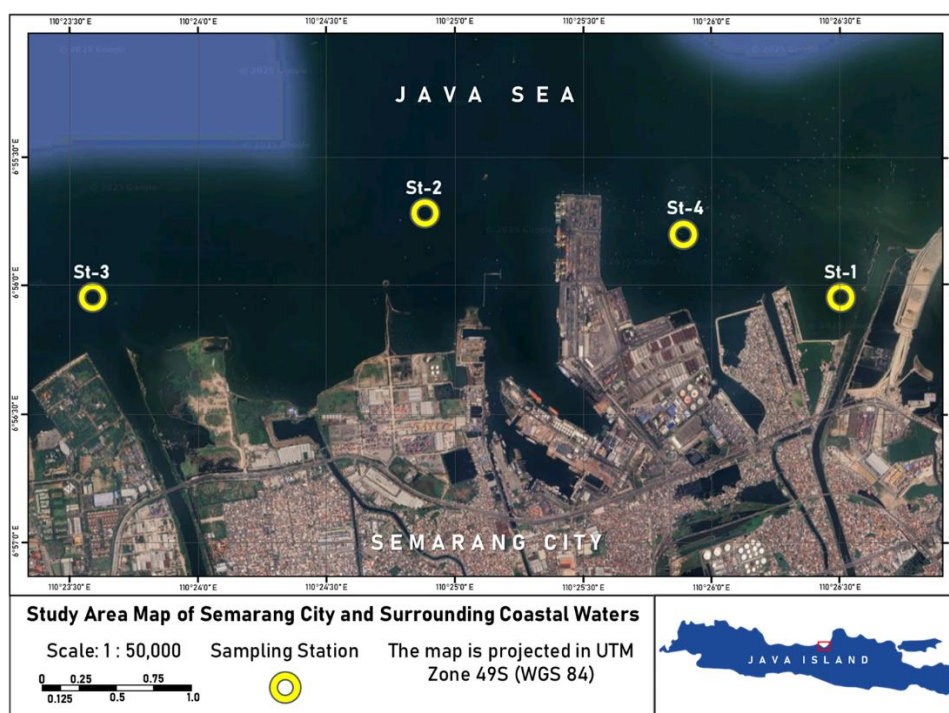


Figure 1. Study Area Map of Semarang City and Surrounding Coastal Waters

Mussels were randomly collected at each station during both sampling periods to represent local population conditions over time. Specimens were harvested live by local fishers and immediately transported in cooled containers to maintain viability. All individuals remained alive until morphometric measurements were conducted.

Water-quality parameters measured in situ included temperature ($^{\circ}\text{C}$), salinity (PSU), pH, dissolved oxygen (mg L^{-1}), water transparency (m), and depth (m). Measurements were conducted using standard instruments: a digital thermometer (Hanna Instruments) for temperature, a refractometer (Atago, Japan) for salinity, a portable pH meter

(Hanna Instruments) for pH, and a dissolved oxygen (DO) meter (YSI Pro20, USA) for DO. Water transparency was measured using a Secchi disk, and depth was determined using a graduated rope. All measurements followed Indonesian National Standard (SNI) procedures. Additional environmental data, including current speed, current direction, and rainfall, were obtained from records of the Semarang Maritime Climatology, Meteorology, and Geophysics Agency.

2.2. Study area and station selection

Sampling stations were selected using purposive sampling, a technique for determining samples based on

specific considerations, in which locations were chosen based on differences in environmental conditions and anthropogenic influences expected to affect the physical water parameters and morphometric traits of green mussels (Herawati et al., 2021). The geographic coordinates of all sampling stations were recorded using a Global Positioning System (GPS). Four sampling stations were established along the northern coast of Semarang (Figure 1) to represent distinct human activities, as follows:

- Station 1-East Banjir Kanal Estuary (coordinate 6°56'32.68" S, 110°26'30.11" E.): Represents industrial influences and is located at the confluence of the Banger and Tenggang Rivers.
- Station 2-Tanjung Emas Port (coordinate 6°56'13.3" S, 110°24'52.3" E): Represents port-related activities.
- Station 3-West Banjir Kanal Estuary (coordinate 6°56'33.0" S, 110°23'34.0" E): Represents industrial influences and is located at the confluence of the Garang River.
- Station 4-Aquaculture Area (coordinate 6°56'18.45" S, 110°25'53.19" E.): Represents aquaculture activities associated with green mussel farming.

2.3. Sample collection

Green mussels were collected at 0.5–2.0 m depth with assistance from local fishers. Sampling was conducted between 07:00 and 11:00 during low tide to standardize conditions and ensure consistent access across stations.

2.4. Water Quality and Morphometric measurements

In situ physical–chemical parameters were measured following Indonesian National Standards (SNI): temperature (SNI 06-6989.23-2005; thermometer), salinity (SNI 7644:2010; refractometer), transparency (SNI 7644:2010; Secchi disk), pH (SNI 06-6989.11-2004; pH meter), and dissolved oxygen (SNI 06-6989.14-2004; DO meter).

Water depth was measured manually using a graduated rope marked at 10 cm intervals. Water samples

Pangalasan et al., 2026. Morphometric Responses of the Green Mussel... were collected using a Nansen bottle. Both measurements were conducted at each station during each sampling period. Morphometric measurements followed the protocol of Risma et al. (2025) and included shell length, shell height, shell width, total weight, and soft-tissue (wet) weight. Before measurement, mussels were cleaned of barnacles, epiphytes, and attached debris; shell dimensions were recorded with calipers (cm), and weights were measured using a digital balance (g).

2.5. Data Analysis

All data were analyzed using nonparametric statistical methods due to they did not meet the normality assumptions based on the Kolmogorov–Smirnov and Shapiro–Wilk tests. Differences in water-quality parameters and mussel morphometrics between the two sampling periods (September and October) were assessed using the Mann–Whitney U test (Deswan et al., 2025), while spatial differences among sampling stations (Stations 1–4) were examined using the Kruskal–Wallis test. Relationships between water-quality parameters (independent variables) and morphometric traits (dependent variables) were evaluated using Spearman’s rank correlation analysis. Correlation strength (ρ) was interpreted following Prion and Haerling (2014): negligible (0.00–0.20), weak (0.21–0.40), moderate (0.4–0.61), strong (0.61–0.80), and very strong (0.81–1.00). All statistical analyses were performed using IBM SPSS Statistics 22, and heatmap visualizations were generated using Python in Google Colab.

3. Results

3.1. Water Quality Dynamics

Water quality parameters varied among sampling stations. Most parameters were within the optimal ranges for green mussel survival; however, current velocity exceeded the recommended threshold. Rainfall does not have a defined optimal range related to the physiological requirements of green mussels and is therefore presented descriptively (Table 1).

Table 1. Physical water parameters of the northern Semarang coastal waters measured at four stations across two sampling periods.

Physical water parameters	Station				Optimal ranges for green mussel survival
	1	2	3	4	
Temperature (°C)	30.35 ± 1.9	30.9 ± 1.27	31.2 ± 0.42	32.4 ± 0.14	29-30 ^{a)}
Salinity (‰)	31.5 ± 3.53	30 ± 5.65	28 ± 2.82	28 ± 2.82	18-33 ^{b)}
pH	7.75 ± 0.07	7.7 ± 0	7.7 ± 0.14	7.6 ± 0.14	7-9 ^{a)}
Dissolved Oxygen (mg/l)	4.37 ± 1.88	6.23 ± 0.57	5.77 ± 0.16	5.6 ± 0.21	>2-12 ^{b)}
Water Transparency (m)	0.49 ± 0.1	1.55 ± 0.28	0.91 ± 0.12	0.8 ± 0.07	≥0,02 ^{c)}
Depth (m)	1.4 ± 0.56	3.02 ± 0.31	3.5 ± 0.7	2.72 ± 0.03	
Current Speed (cm/s)	5 ± 2.82				10 – 30 ^{e)}
Rainfall (mm)	79.7 ± 50.48				-

Footnotes: a) Hakim et al. (2024); b) Sagita et al. (2018); c) Firdaus et al. 2023; d) Rahayu et al. (2024) e) Arsandi et al. (2017).

Table 2. Results of Mann–Whitney and Kruskal–Wallis tests for in situ water parameters across sampling periods and stations.

In situ water parameters	ρ value (Mann – Whitney)	ρ value (Kruskal – Wallis)
Temperature	$\rho > 0.05$ (Not Significant)	$\rho > 0.05$ (Not Significant)
Salinity	$\rho < 0.05$ (Significant)	$\rho > 0.05$ (Not Significant)
pH	$\rho > 0.05$ (Not Significant)	$\rho > 0.05$ (Not Significant)
Dissolved Oxygen	$\rho > 0.05$ (Not Significant)	$\rho > 0.05$ (Not Significant)
Water Transparency	$\rho > 0.05$ (Not Significant)	$\rho > 0.05$ (Not Significant)
Depth	$\rho > 0.05$ (Not Significant)	$\rho > 0.05$ (Not Significant)

Table 2 indicates that most in situ water quality parameters did not differ significantly among stations across the two sampling periods ($\rho > 0.05$). In contrast, salinity exhibited a statistically significant difference between the two sampling periods ($\rho < 0.05$).

3.2. Spatial and Temporal Variations in Morphometrics

Based on Table 3, green mussels collected from four stations across the two sampling periods generally exhibited a reduction in body size across all morphometric traits. Station 4 was the only exception, showing an increase in all

measured morphometric parameters. This pattern is likely influenced by the station's characteristics as an aquaculture

Table 3. Morphometric characteristics of *Perna viridis*, measured at different stations across two sampling periods.

Station	Sampling Period	N	Shell Length (cm)	Shell Height (cm)	Shell Width (cm)	Total Weight (g)	Soft Tissue Weight (g)
1	September	100	4.92 ± 1.63	2.4 ± 0.66	1.59 ± 0.27	10.64 ± 8.58	3.08 ± 2.3
	October	100	3.16 ± 0.67	1.76 ± 0.2	0.99 ± 0.32	3.57 ± 1.91	1.38 ± 0.78
2	September	100	4.39 ± 0.67	1.41 ± 0.23	2.18 ± 0.27	6.56 ± 2.02	2.17 ± 0.83
	October	100	2.75 ± 0.33	1.4 ± 0.14	0.76 ± 0.23	2.07 ± 0.4	0.82 ± 0.33
3	September	100	4.07 ± 0.78	2.07 ± 0.43	1.23 ± 0.41	6.18 ± 3.33	2.04 ± 0.95
	October	100	3.58 ± 0.39	1.36 ± 0.36	0.85 ± 0.18	3.92 ± 0.94	1.49 ± 0.59
4	September	100	4.54 ± 0.67	2.27 ± 0.32	1.28 ± 0.21	6.86 ± 2.49	2.77 ± 1.19
	October	90	4.76 ± 0.77	1.11 ± 0.19	1 ± 0.24	8.62 ± 3.13	3.55 ± 1.4

Table 4. Statistical comparison of *Perna viridis* morphometric traits among sampling stations and periods using Mann–Whitney and Kruskal–Wallis tests.

Morphometric Traits of <i>Perna viridis</i>	p value (Mann-whitney)	ρ value (Kruskal wallis)
Shell Length	ρ < 0.05 (Significant)	ρ < 0.05 (Significant)
Shell Height	ρ < 0.05 (Significant)	ρ < 0.05 (Significant)
Shell Width	ρ < 0.05 (Significant)	ρ < 0.05 (Significant)
Total Weight	ρ < 0.05 (Significant)	ρ < 0.05 (Significant)
Soft Tissue Weight	ρ < 0.05 (Significant)	ρ < 0.05 (Significant)

Statistical analyses (Table 4) using the Mann–Whitney and Kruskal–Wallis tests demonstrated significant differences in green mussel morphometric traits among stations and between sampling periods (ρ < 0.05). Correlation analysis (Table 5) indicated substantial variability in the strength and significance of relationships between water parameters and morphometric traits. Most parameters were

significantly associated with all traits (ρ < 0.05), whereas temperature showed limited significance, particularly for shell length, total weight, and soft tissue weight. Correlations were predominantly negative, except for salinity, which consistently exhibited strong positive correlations across all morphometric traits, while pH showed the weakest relationships.

Table 5. Spearman's correlation coefficients between water parameters and morphometric traits of *Perna viridis*.

Water Parameters	Morphometric Traits				
	Shell Length (cm)	Shell Height (cm)	Shell Width (cm)	Total Wet Weight (g)	Soft Tissue Weight (g)
Temperature (°C)	ρ = - 0.063 (p > 0.05)	ρ = - 0.388 (p < 0.05)	ρ = - 0.318 (p < 0.05)	ρ = - 0.069 (p > 0.05)	ρ = 0.059 (p > 0.05)
Salinity (‰)	ρ = 0.401 (p < 0.05)	ρ = 0.764 (p < 0.05)	ρ = 0.673 (p < 0.05)	ρ = 0.405 (p < 0.05)	ρ = 0.285 (p < 0.05)
pH	ρ = - 0.118 (p < 0.05)	ρ = - 0.255 (p < 0.05)	ρ = - 0.120 (p < 0.05)	ρ = - 0.104 (p < 0.05)	ρ = - 0.154 (p < 0.05)
Dissolved Oxygen (mg/l)	ρ = - 0.183 (p < 0.05)	ρ = - 0.462 (p < 0.05)	ρ = - 0.322 (p < 0.05)	ρ = - 0.226 (p < 0.05)	ρ = - 0.228 (p < 0.05)
Transparency (m)	ρ = - 0.175 (p < 0.05)	ρ = - 0.113 (p < 0.05)	ρ = - 0.173 (p < 0.05)	ρ = - 0.244 (p < 0.05)	ρ = - 0.238 (p < 0.05)
Depth (m)	ρ = - 0.156 (p < 0.05)	ρ = - 0.203 (p < 0.05)	ρ = - 0.233 (p < 0.05)	ρ = - 0.195 (p < 0.05)	ρ = - 0.195 (p < 0.05)

3.3. Correlation between Water Quality and Morphometric Traits

Figure 2 shows that salinity consistently exhibited moderate to the strongest positive correlations with all green mussel morphometric traits, particularly shell height (ρ = 0.764). In contrast, dissolved oxygen displayed a moderate negative correlation (ρ = -0.462), whereas temperature, water transparency, and depth showed weak and mostly negative associations. Overall, the heatmap indicates variable strengths and directions of relationships between water parameters and green mussel morphometry.

4. Discussion

Based on in situ measurements and secondary current-speed data (Table 1), water quality parameters varied

among stations but generally remained within optimal ranges for green mussel survival. Water temperature at all stations was non-limiting, as excessively high temperatures—which can induce physiological stress, reduce filtration rates, and impair cardiovascular function in bivalves (Boroda et al., 2020; Azizan et al., 2023)—were not observed. Salinity and pH values across all stations also fell within ideal ranges, indicating favorable conditions for osmotic regulation, reproduction, larval development, shell formation, and calcification, as extreme salinity and unsuitable pH are known to disrupt these processes and increase juvenile vulnerability (Copeado et al., 2025; Poumozaffar et al., 2025).

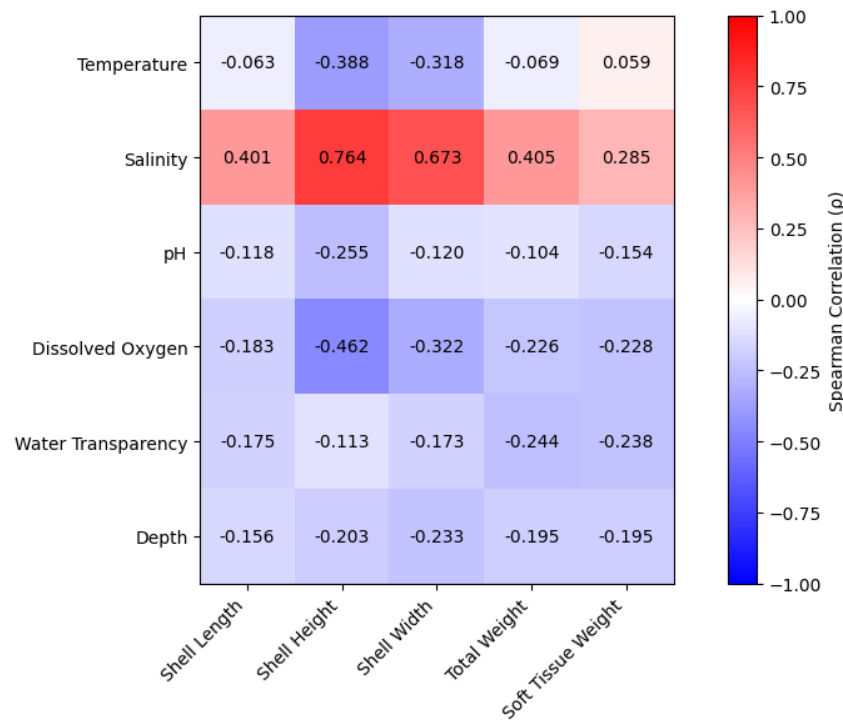


Figure 2. Heatmap of Spearman's correlation coefficients between water quality parameters and morphometric traits of *Perna viridis*.

Morphometric data (Table 3) indicated a general reduction in green mussel size at most stations, except at Station 4, where increases were observed, likely reflecting greater stability of environmental parameters that support optimal metabolic activity. Environmental variability is known to increase mussel mortality (Picoy-Gonzales and Laureta, 2022), suggesting that differences in environmental stability among stations contributed to the observed morphometric patterns. Statistical analyses using the Mann–Whitney and Kruskal–Wallis tests (Table 4) revealed significant differences in morphometric traits among stations and sampling periods ($p < 0.05$), with the large sample size ($n = 790$) enhancing the sensitivity of the tests to detect small effect sizes, consistent with the relationship between sample size and statistical power described by Gumpili and Das (2022).

Spearman's correlation analysis (Table 5) identified salinity as the dominant factor influencing green mussel morphometric traits, showing strong positive correlations with shell height ($\rho = 0.764$, $p < 0.05$) and shell width ($\rho = 0.673$, $p < 0.05$). This pattern reflects the role of salinity in regulating mineral deposition, shell microstructure, and organic matrix formation, consistent with findings that mussels inhabiting high-salinity environments generally develop thicker shells (Clark et al., 2020).

Dissolved oxygen (DO) showed negative correlations with all morphometric traits, reflecting local-scale hydrodynamic conditions rather than direct physiological stress, as higher DO is typically associated with stronger currents that increase the energetic cost of attachment and reduce energy allocation to shell growth (Fitroh et al., 2025). Shell height emerged as the most responsive morphometric trait to environmental variation, consistent with its sensitivity to salinity-driven shell size and shape regulation (Moran et al., 2022) and its anatomical growth pattern, in which radial shell accretion and active biomineral deposition at the ventral margin directly contribute to shell height expansion (Dobra et al., 2024).

Heatmap analysis (Figure 2) further highlighted salinity as a key driver, forming a strong cluster with shell height and shell width, underscoring its role in osmoregulation and mineral deposition processes (Suárez-Mozo et al., 2023), whereas DO and temperature clustered as hydrodynamically influenced parameters linked to water mass dynamics (Zanella et al., 2025).

This study demonstrates that salinity is the dominant environmental factor with important ecological implications, particularly for the use of green mussels as an early warning indicator of environmental quality. Green mussels are highly responsive to osmotic stress and variations in water mass (Vereycken and Aldridge, 2023); thus, changes in morphometric traits, especially shell height, can serve as effective indicators of extreme salinity fluctuations driven by freshwater inputs and coastal dynamics (Adjovu et al., 2023). From a management perspective, Station 4 represents the most suitable site due to its stable salinity conditions, consistent with previous findings identifying salinity as a key determinant of bivalve growth (Yanti et al., 2022), and highlighting its potential for aquaculture development and long-term water-quality monitoring.

However, interpretation of these findings is constrained by several technical limitations, including limited temporal coverage that does not fully capture seasonal variability in the Semarang coastal system, the absence of physiological indicators such as gonadal condition, sex ratio, and stress biomarkers, and reliance on secondary data for current speed, which limits the resolution of micro-scale hydrodynamic differences among stations.

5. Conclusions

This study demonstrates that salinity is the dominant environmental factor shaping morphometric variation in *Perna viridis*, with shell height emerging as the most sensitive trait and a promising biological indicator of environmental change. Station 4, characterized by more stable salinity conditions, provides the most suitable habitat for optimal green mussel growth. These findings reveal clear spatial

differences in habitat suitability and offer valuable insights for coastal management and the sustainable development of green mussel aquaculture along the northern coast of Semarang. Future coastal management should integrate shell height monitoring as a practical early-warning tool, where significant reductions in shell growth may indicate shifts in water mass stability and potential environmental deterioration.

Ethics approval

The study complied with Indonesian animal welfare regulations, and no specific permits were required for the sampling of marine biota. All procedures were conducted in accordance with the relevant institutional and national guidelines governing the use of aquatic organisms in research

Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Author contributions

Maurina Chasimira Edenie Pangalasan contributed to research conceptualization, data collection, data curation, methodology, project administration, visualization, formal analysis, and writing of the original manuscript. Bambang Yulianto and Agoes Soegianto provided supervision, validation, and manuscript review and editing. Shendy Naumi Tamba and Carolyn Melissa Payus assisted with data collection, resources, and project administration.

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Declaration of competing Interest

The authors declare no competing interests.

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