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Allometric relationships of *Donax* sp. collected from Sungai Janggut: ecological insights, environmental stress, and coastal conservation implications

Abstract

This study investigates the allometric relationships between shell length, width, height, and weight of *Donax* sp. collected from Sungai Janggut, (on 7 May, 2024), Malaysia, across three groups (Group 1: N=429; Group 2: N=342; Group 3: N=329; Group All: N=1100). Pearson's correlation analysis revealed significant differences among the groups, with Group 3 displaying strong positive correlations among allometric parameters, particularly between shell length, width, and weight, indicating optimal growth conditions. Conversely, Groups 1 and 2 exhibited weaker correlations, suggesting growth disruptions likely due to environmental stressors or suboptimal habitat conditions. Factor analysis further confirmed these patterns, with shell length and width as primary contributors to shell weight, while shell height showed negative or minimal influence. Multiple regression analysis identified shell length as the dominant predictor of shell weight, particularly in Group 3, followed by shell width, while height contributed negatively in most groups. The results provide ecological insights into the adaptive strategies of *Donax* sp. under varying environmental pressures and highlight their role as bioindicators of ecosystem health. From a coastal conservation perspective, these findings underscore the need to protect intertidal habitats to sustain *Donax* sp. populations and the essential ecosystem services they provide.

Keywords allometric relationships, bivalves, environmental stress, coastal conservation, bioindicators

Volume 9 Issue 4 - 2024

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Received: December 12, 2024 | **Published:** December 23, 2024

Introduction

Bivalves, a class of molluscs inhabiting intertidal and coastal zones, play a critical role in marine ecosystems due to their contributions to nutrient cycling, sediment stabilization, and water filtration.[1,2] Their growth patterns and allometric relationships, such as the relationships between shell dimensions (length, width, height) and weight, are often influenced by environmental conditions and ecological pressures.[3,4] Understanding these relationships provides insights into the health of bivalve populations and the quality of their habitats, making them excellent bioindicators for monitoring ecosystem changes.[5,6] Given their ecological importance and economic significance in fisheries and aquaculture, studying allometric parameters is essential for the sustainable management and conservation of bivalve species.[7,8] Variations in allometric relationships across different bivalve populations are often driven by environmental stressors such as water quality, food availability, sediment composition, and anthropogenic impacts.[2,9–10] These factors influence the allocation of energy towards shell growth and biomass accumulation, leading to differences in the correlations between shell length, width, height, and weight. For instance, in stable and nutrient-rich environments, bivalves exhibit synchronized growth, with strong positive relationships among allometric parameters.[11,12] In contrast, under stressful or dynamic conditions, growth patterns may become inconsistent, weakening these correlations.[5,13] Investigating such variations helps identify factors affecting bivalve populations and their adaptive strategies, which are crucial for ecosystem resilience.

Factor analysis and multiple regression models are powerful tools for exploring interrelationships between allometric parameters and identifying key contributors to shell weight and growth patterns. These methods isolate the factors that significantly influence shell weight and explain variations across populations.[3,14] For instance, shell length and width are often dominant predictors of weight, while shell height may show limited or negative contributions depending on environmental conditions.[4,15] By applying these methods, this study aims to uncover the dominant growth factors and their ecological significance in small bivalves, offering insights into their adaptive strategies under varying environmental pressures. The intertidal zone of Sungai Janggut, Malaysia, provides an ideal site for examining *Donax* sp. allometric relationships due to its diverse and fluctuating environmental conditions, including salinity, sediment load, and anthropogenic pressures. These stressors have been shown to impact *Donax* sp. growth and morphology in other regions, emphasizing the importance of habitat-specific studies.[16,7] While previous research has highlighted the ecological significance of allometric parameters and their role in *Donax* sp. adaptations,[3,17] few studies have explored how these relationships vary under differing environmental conditions. This study addresses that gap by analysing the correlations, factor loadings, and regression outcomes of shell dimensions and weight across three distinct *Donax* sp. groups, shedding light on the interplay between environmental factors and *Donax* sp. growth dynamics. The objectives of this study are to

I. Analyze the allometric relationships (shell length, width, height, and weight) of *Donax* sp. across three groups collected from Sungai Janggut.

II. Identify the dominant predictors of shell weight using multiple regression analysis.

III. Provide ecological insights into the growth dynamics and environmental stress adaptations of these Donax population.

The findings are significant for coastal conservation, as they emphasize the role of *Donax* sp. as bioindicators of environmental health and highlight the need to protect intertidal habitats to sustain *Donax* sp. populations and the critical ecosystem services they provide.

Materials and methods

The samples were collected on 7 May 2024 from the intertidal zone of Sungai Janggut (Selangor), located along the west coast of Peninsular Malaysia. This region was selected due to its ecological significance and exposure to diverse environmental conditions, including fluctuating salinity, sediment load, and anthropogenic activities. The collected *Donax* sp. were thoroughly cleaned to remove sediment and biofouling before measurement. Four allometric parameters were recorded for each individual. The allometric parameters measured for each *Donax* sp. included shell length, width, height, and weight. Shell length (cm) refers to the maximum anterior-posterior distance of the shell, while shell width (cm) represents the maximum lateral distance across the shell. Shell height (cm) is the maximum vertical distance from the base to the highest point of the shell. Shell weight (g) was recorded as the total weight of the shell after drying to remove excess moisture, ensuring accurate and consistent measurements. All measurements were taken with precision instruments to ensure accuracy. Vernier callipers, with an accuracy of 0.01 cm, were used for shell dimensions, while an analytical balance with a precision of 0.001 g was used to measure shell weight. Each parameter was measured three times per individual, and mean values were calculated to reduce measurement error. *Donax* sp. were divided into three distinct groups to capture potential environmental and habitat variability: Group 1 ($N = 429$), Group 2 ($N = 342$), and Group 3 ($N = 329$). The combined dataset comprised a total of 1100 individuals. Sampling was carried out during low tide across designated transects to ensure representative coverage of the study area.

Descriptive statistics, including mean, standard deviation, skewness, kurtosis, minimum, and maximum values, were calculated for all parameters to understand the distribution and variability of shell dimensions and weight across the three groups. Pearson's correlation coefficients were calculated to evaluate the relationships between shell length, width, height, and weight for each group. Statistical significance was set at $p < 0.05$ to identify meaningful relationships between the allometric parameters. Factor analysis using the Promax rotation method was performed to uncover underlying factors contributing to the variation in shell dimensions and weight. Factor loadings greater than 0.4 were considered significant for interpreting the relationships between parameters. Multiple regression analysis was conducted to determine the contributions of shell length, width, and height (independent variables) to shell weight (dependent variable). Regression models were generated separately for each group and for the combined dataset. Beta coefficients were used to evaluate the strength and direction of the predictors, with statistical significance established at $p < 0.05$. Prior to analysis, the dataset was validated for normality using the Shapiro-Wilk test, and potential outliers were identified and examined using boxplots. All statistical analyses were performed using JASP software. Results were presented in tables, and density plots were used to visualize the distribution patterns of shell parameters for each group. All fieldwork and data collection adhered to ethical research practices, with appropriate permissions obtained for sample collection in the study area. *Donax* sp. were handled with care throughout the study, and unused samples were returned to their natural habitat to minimize ecological disturbance.

Results

Descriptive statistics

Descriptive Statistics of shell lengths, shell widths, shell heights, and shell weights of *Donax* sp. are presented in Table 1. For Group 1, consisting of 429 samples, demonstrated lower mean values for all measured parameters of shell dimensions and weight. The mean shell length was 1.779 cm, while the mean shell width was 1.620 cm, indicating relatively smaller shells compared to other groups. The mean shell height was 0.540 cm, and the mean weight was 0.370 g, showing lighter and shorter dimensions overall. The standard deviation ranged from 0.147 for shell height to 0.492 for shell width, indicating a moderate spread in the data. The skewness values were negative for shell length (-1.023) and shell height (-0.119), suggesting a slight leftward asymmetry. In contrast, shell width showed a skewness of 0.398, indicating rightward asymmetry, while shell weight exhibited a near-symmetrical skewness value of 0.103. Kurtosis values close to zero for length (-0.137) and height (-0.216) suggested light-tailed distributions, while shell weight displayed slight peakedness (0.231). The Shapiro-Wilk test revealed significant deviations from normality for all parameters ($p < 0.001$), reinforcing non-normal distributions. The range for shell length spanned 0.900 to 2.000 cm, while the weight varied between 0.110 and 0.760 g. For Group 2, with 342 samples, showed larger mean values for shell dimensions compared to Group 1. The mean shell length was 2.153 cm, and the mean shell width was 1.445 cm, suggesting slightly broader shells. Shell height and weight were measured at 0.585 cm and 0.372 g, respectively. The standard deviation was lowest for weight (0.092) and highest for shell width (0.203), reflecting low variability for weight measurements and moderate variability for width.

Skewness values indicated a near-symmetrical distribution for shell length (-0.119) and height (-0.459), whereas shell width had a leftward skewness of -1.081. Interestingly, shell weight showed a positive skewness of 0.461, suggesting a heavier tail in weight distributions. The kurtosis values were most prominent for shell width (2.935) and weight (0.594), indicating heavier tails. The Shapiro-Wilk test confirmed significant deviations from normality ($p < 0.001$) for all parameters. The shell length ranged between 1.200 and 2.200 cm, while the weight spanned 0.070 to 0.687 g.

Table 1 Descriptive statistics of shell lengths, shell widths, shell heights, and shell weights of *donax* sp. collected from Sungai Janggut (Group 1, N= 429; Group 2, N= 342; Group 3, N= 329; Group All= 1100)

	Group 1 Length-1	Group 1 Width-1	Group 1 Height-1	Group 1 Weight	Group 2 Length-2	Group 2 Width-2	Group 2 Height-2	Group 2 Weight-2
Mean	1.779	1.62	0.54	0.37	2.153	1.445	0.585	0.372
Std. Deviation	0.269	0.492	0.147	0.109	0.05	0.203	0.115	0.092
Skewness	-1.023	0.398	-0.119	0.613	-0.119	-1.081	-0.459	0.461
Kurtosis	-0.137	-0.75	-0.216	0.231	-1.996	2.935	0.337	0.594
Shapiro-Wilk	0.798	0.945	0.954	0.975	0.636	0.862	0.914	0.984
P-value of Shapiro-Wilk	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Minimum	0.9	0.6	0.2	0.131	2.1	0.6	0.3	0.07
Maximum	2	2.9	0.9	0.76	2.2	2.3	0.9	0.687
	Group 3 Length-3	**Group 3 Width-3**	**Group 3 Height-3**	**Group 3 Weight-3**	**Group All Length All**	**Group All Width All**	**Group All Height All**	**Group All Weight All**
Mean	2.393	1.593	0.663	0.431	2.079	1.558	0.591	0.389
Std. Deviation	0.121	0.182	0.098	0.11	0.316	0.35	0.134	0.108
Skewness	1.915	-1.741	-0.861	0.77	-0.919	0.619	-0.531	0.639
Kurtosis	4.893	5.948	1.706	1.802	1.106	1.382	0.127	0.982
Shapiro-Wilk	0.742	0.857	0.86	0.964	0.926	0.937	0.93	0.979
P-value of Shapiro-Wilk	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Minimum	2.3	0.6	0.3	0.167	0.9	0.6	0.2	0.07
Maximum	3	2	0.9	0.866	3	2.9	0.9	0.866

For Group 3, which included 329 samples, displayed the largest mean values among all groups. The mean shell length was 2.393 cm, while the mean width was 1.593 cm, suggesting larger and wider shells. Shell height and weight were also greater at 0.663 cm and 0.431 g, respectively. The standard deviation values were lowest for shell height (0.098) and highest for width (0.182), reflecting minor variability in height but moderate variation in width.

The skewness for shell length was notably high (1.915), indicating a strong positive asymmetry, while width and height had negative skewness values of -1.741 and -0.861, respectively. Kurtosis values were particularly high for shell length (4.893) and shell width (5.948), suggesting sharp peaks in these distributions. Similar to previous groups, the Shapiro-Wilk test revealed non-normality across all parameters ($p < 0.001$). Shell length measurements ranged between 2.300 and 3.000 cm, while shell weight spanned 0.187 to 0.866 g.

3.4 Combined Group (Group All) Descriptive Statistics. When combining all samples (N=1100), the overall means for shell length, width, height, and weight were 2.079 cm, 1.558 cm, 0.591 cm, and 0.389 g, respectively. These combined values reflect an average across all groups, with shell dimensions and weights moderate in comparison. The standard deviation for the combined data ranged from 0.108 (weight) to 0.350 (width), demonstrating a consistent variability trend observed across individual groups. The skewness for shell length (-0.919) and shell height (-0.531) revealed slight leftward asymmetry, while shell weight displayed a small positive skewness (0.639). Kurtosis values were relatively lower compared to Group 3, with the highest being for shell weight (0.982). The Shapiro-Wilk test confirmed significant non-normality for all measurements ($p < 0.001$). The combined minimum and maximum values were 0.900 to 2.900 cm for length and 0.070 to 0.866 g for weight.

Correlation analysis between allometric parameters in Table 2 and Figure 1

Table 2 Pearson's correlation coefficients between the four allometric parameters of the *donax* sp. collected from Sungai Janggut, for Group 1 (N= 429), Group 2 (N= 342), Group 3 (N= 329), and Group All (N= 1100)

	Group 1 Length	Group 1 Width	Group 1 Height	Group 1 Weight		Group 2 Length-2	Group 2 Width-2	Group 2 Height-2	Group 2 Weight-2
Length	—				Length-2	—			
Width	-0.636	—			Width-2	0.163	—		
Height	-0.295	0.611	—		Height-2	0.15	0.549	—	
Weight	-0.039	-0.039	-0.245	—	Weight-2	0.029	-0.176	-0.201	—
	Group 3 Length-3	**Group 3 Width-3**	**Group 3 Height-3**	**Group 3 Weight-3**		**Group All Length All**	**Group All Width All**	**Group All Height All**	**Group All Weight All**
Length-3	—				Length All	—			
Width-3	0.293	—			Width All	-0.334	—		
Height-3	0.32	0.43	—		Height All	0.224	0.494	—	
Weight-3	0.367	0.21	0.076	—	Weight All	0.202	-6.829×10^{-4}	-0.044	—

Note: values in bold are significant at P< 0.05.

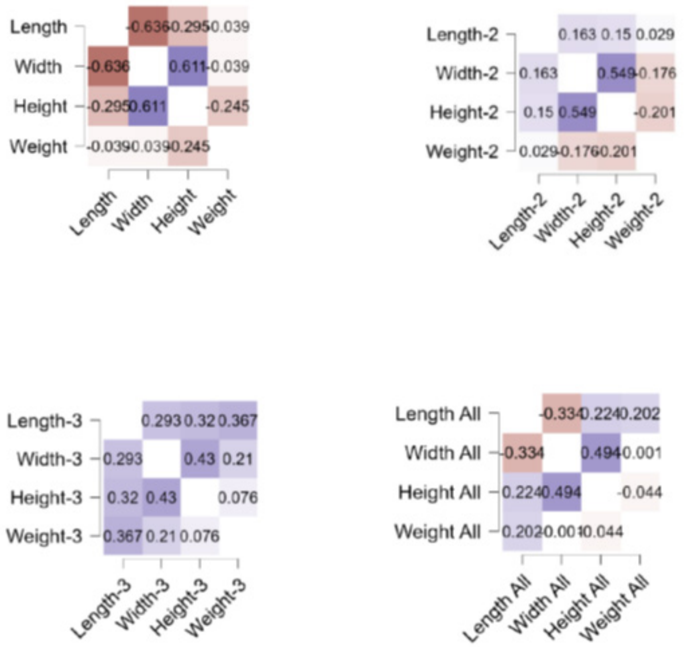

Figure 1 Heatmaps of pearson's correlation coefficients between the four allometric parameters of *donax* sp. collected from sungai janggut, for Group 1 (N= 429), Group 2 (N= 342), Group 3 (N= 329), and Group All (N= 1100).

The Pearson's correlation coefficients between the four allometric parameters are presented in Table 2 and Figure 1. In Group 1, significant correlations were observed between shell length and shell width ($r = 0.636$, $p < 0.05$), indicating a strong positive relationship between these two parameters. However, the correlations between length and height ($r = -0.089$) and length and weight ($r = -0.039$) were weak and non-significant. Similarly, shell width showed weak correlations with height ($r = -0.309$) and weight ($r = -0.039$), highlighting limited relationships among these parameters. For Group 2, significant positive correlations were observed between shell width and weight ($r = 0.549$, $p < 0.05$) and between height and weight ($r = 0.176$, $p < 0.05$). The correlation between length and width ($r = 0.163$) was weaker but still positive, suggesting a mild association. Conversely, the relationships between length and height ($r = 0.150$) and length and weight ($r = 0.029$) were weak and non-significant.

Group 3 demonstrated stronger and more consistent relationships among the allometric parameters. Shell length exhibited a moderate correlation with shell width ($r = 0.293$) and a stronger positive correlation with shell weight ($r = 0.367$, $p < 0.05$). Width and height were weakly correlated ($r = 0.320$), while height and weight showed a moderate positive relationship ($r = 0.216$, $p < 0.05$). These findings suggest greater interdependence of allometric parameters in Group 3 compared to Groups 1 and 2. When all groups were combined (N=1100), significant positive correlations were observed between shell length and shell width ($r = 0.334$, $p < 0.05$), as well as between shell length and shell weight ($r = 0.202$, $p < 0.05$). Shell width also showed moderate correlations with weight ($r = 0.494$, $p < 0.05$). Notably, the relationship between shell height and weight was weak and non-significant ($r = -0.044$), suggesting limited dependence of weight on shell height across the combined dataset.

Factor analysis of allometric parameters

From Table 3, For Group 1, the factor analysis identified three distinct factors. Factor 1 had the highest loadings for shell length (0.785) and shell height (0.700), indicating their dominant contributions to this factor. Factor 2 was primarily associated with shell width (0.581), suggesting a separate dimension for this parameter. Factor 3 was linked to shell weight, with a moderate factor loading of 0.444. Notably, the negative loading for shell width in Factor 1 (-0.508) indicates that shell width does not align positively with shell length and height, highlighting morphological differences within this group. In Group 2, two primary factors were identified. Factor 1 was dominated by shell width (0.558) and shell height (0.447), highlighting their strong combined influence on shell morphology. Factor 2 exhibited a strong negative loading for shell weight (-0.400), indicating an inverse relationship between weight and the other parameters. These findings suggest a clear distinction between shell size (length, width) and shell weight in Group 2, with weight behaving independently from the size dimensions. For Group 3, the factor analysis revealed a clearer relationship between the parameters. Factor 1 was strongly associated with shell length (0.658), shell width (0.616), and shell weight (0.484), indicating a strong positive relationship among these variables. In contrast, Factor 2 was dominated by shell height, with a high loading of 0.647, reflecting its independent contribution. These results suggest that, in Group 3, shell length, width, and weight are closely interrelated, whereas shell height forms a distinct and separate dimension. For the combined dataset (N = 1100), three distinct factors were identified. Factor 1 displayed the strongest loadings for shell width (0.855) and shell height (0.836), indicating their major contributions to this factor. Factor 2 was primarily associated with shell weight and showed a moderate negative loading for shell height (-0.428), reflecting an inverse relationship. Factor 3 included shell length, with a loading of 0.546, highlighting its distinct and separate dimension in the overall dataset.

Citation: Erliana I, Bahri AAAS, Shamsir DS, et al. Allometric relationships of *Donax sp.* collected from Sungai Janggut: ecological insights, environmental stress, and coastal conservation implications. *MOJ Biol Med.* 2024;9(4):129–137. DOI: 10.15406/mojbm.2024.09.00229

Table 3 Factor loadings from factor analysis in the four allometric parameters of *donax* sp. collected from Sungai Janggut, for Group 1 (N= 429), Group 2 (N= 342), Group 3 (N= 329), and Group All (N= 1100)

Group 1	**Factor 1**	**Factor 2**	**Factor 3**	**Group 2**	**Factor 1**	**Factor 2**	**Factor 3**
Length	0.785			Width-2	0.558		
Width	-0.508	0.581		Height-2		0.447	
Height		0.7		Weight-2		-0.4	
Weight			0.444	Length-2			
Group 3	Factor 1	Factor 2	Factor 3	Group All	Factor 1	Factor 2	Factor 3
Length-3	0.658			Width All	0.855		
Width-3	0.616			Height All	0.723	-0.428	
Height-3		0.647		Weight All		0.836	
Weight-3			0.484	Length All			0.546

Note: Applied rotation method is promax

Multiple regression analysis of shell weight

As shown in Table 4, in Group 1 (N=429), the regression analysis revealed that shell length (β = 0.496) had a significant positive relationship with shell weight, highlighting its dominant contribution. In contrast, shell width (β = 0.031) showed a weak positive influence, though it was not statistically significant. Interestingly, shell height (β = -0.256) demonstrated a strong negative relationship with shell weight, indicating that greater shell height reduces overall shell weight. These findings suggest that shell weight in Group 1 is primarily influenced by shell length, while shell height exerts a negative impact. In Group 2 (N=342), the regression analysis showed that shell length (β = 0.126) had a weak positive influence on shell weight, while shell width (β = -0.046) exhibited a weak negative relationship. Shell height (β = -0.124) also contributed negatively, though this relationship was not significant. These results suggest that shell weight in Group 2 is only marginally influenced by shell length, with shell width and height having minimal contributions.

Table 4 Multiple regression analysis with shell weight as dependent variable, while the independent variables included shell length, shell width, and shell height, for *donax* sp. collected from Sungai Janggut, for Group 1 (Weight-1; N= 429), Group 2 (Weight-2; N= 342), Group 3 (Weight-3; N= 329), and Group All (Weight All; N= 1100)

Weight All		**Weight-1**		**Weight-2**		**Weight-3**	
Int	0.161	Int	0.496	Int	0.24	Int	-0.409
Length All	0.111	Length	-0.021	Length-2	0.126	Length-3	0.323
Width All	0.067	Width	0.031	Width-2	-0.046	Width-3	0.09
Height All	-0.18	Height	-0.256	Height-2	-0.124	Height-3	-0.114

Note: Values in bold are significant at P< 0.05.

In Group 3 (N=329), the regression results indicated that shell length (β = 0.323) was the strongest positive predictor of shell weight, while shell width (β = 0.090) had a weak but positive influence. In contrast, shell height (β = -0.114) showed a slight negative contribution. These findings highlight the dominant role of shell length in determining shell weight, with minimal contributions from shell width and height. For the combined group (N=1100), the regression analysis showed that shell length (β = 0.111) and shell width (β = 0.067) had positive and significant contributions to shell weight, whereas shell height (β = -0.180) exhibited a significant negative relationship. These results indicate that shell weight is primarily influenced by the size parameters of length and width, while the negative contribution of height suggests a potential compensatory effect on overall weight.

Discussion

Differences in correlations among group size of bivalves

The observed differences in the correlations of four allometric parameters (shell length, width, height, and weight) among Group 1 (N=429), Group 2 (N=342), and Group 3 (N=329) can be attributed to variations in environmental conditions, growth stages, group sizes, and population dynamics.

Environmental conditions and food availability

Distinct environmental factors in the Sungai Janggut intertidal region, such as water quality, food availability, and sediment composition, likely influenced *Donax* sp. growth across groups. Group 1, exhibiting weaker correlations between shell dimensions and weight, may have experienced suboptimal conditions, including nutrient scarcity, sediment stress, or anthropogenic disturbances. These factors could disrupt even shell development, reducing alignment among parameters. In contrast, Group 3 displayed stronger interrelationships, particularly between shell length, width, and weight, suggesting more favorable environmental conditions conducive to synchronized and proportional growth. Resource availability significantly influences *Donax* sp. group dynamics and size differentiation. Optimal food supply enhances growth rates through improved ingestion and absorption capacities, promoting variability in group size.[22,9] Conversely, food scarcity restricts growth and reduces size diversity within groups, potentially weakening interrelationships among shell dimensions.

Predation pressure and habitat characteristics

Predation pressure further impacts group size correlations. The *Donax* sp. is more vulnerable to predators and may allocate energy toward defence or avoidance strategies at the expense of growth.[18]

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This dynamic influences size distribution and growth patterns within populations, leading to variability across groups. The physical attributes and connectivity of habitats also affect *Donax* sp. distribution, abundance, and group size correlations. Sediment composition and habitat connectivity, such as those seen in floodplains, determine biomass and density patterns.[19] Well-connected habitats generally support larger, more stable, and diverse *Donax* sp. populations.

Functional diversity and habitat type

Variations in growth stages further explain differences in correlations. Group 1, consisting of smaller and lighter shells, likely represents younger individuals whose growth remains inconsistent across dimensions, resulting in weaker correlations with weight. Group 2, characterized by moderate shell size and weight, reflects an intermediate growth phase where dimensions like height may grow disproportionately due to localized conditions. Group 3, comprising larger and heavier shells, represents a mature population with balanced growth patterns. This results in stronger alignment between shell length, width, and weight, contributing to higher correlation strengths. Group size in *Donax* sp. may also depend on habitat type and associated functional diversity. Seagrass beds, for instance, provide structural complexity that supports higher species diversity and functional group richness compared to less structured habitats.[1] This diversity can foster larger, more stable group sizes, enhancing correlations among shell dimensions. Therefore, differences in correlation patterns among *Donax* sp.groups are shaped by environmental conditions, growth stages, population sizes, and morphological adaptations. Group 3 reflects favorable conditions and uniform growth dynamics, while Group 1 and Group 2 demonstrate the effects of environmental stress, uneven development, and population variability. Although direct evidence on group size correlations remains limited, the role of environmental factors, predation, habitat characteristics, and functional diversity provides significant insights. Future studies quantifying these relationships under varying ecological conditions will further clarify their influence on *Donax* sp. group dynamics.

Ecological insights into allometric relationships

The allometric relationships of *Donax* sp. provide valuable insights into their growth strategies, habitat suitability, and ecosystem dynamics, underscoring their critical ecological roles and responses to environmental conditions.

Body size and biomass relationships

Body size serves as a reliable predictor of biomass metrics, including living weight, wet weight, and dry weight. Despite inherent variability among *Donax* sp. populations, body size consistently correlates with biomass, emphasizing its ecological importance.[11] This relationship facilitates biomass estimation, which is crucial for understanding the ecological contributions of *Donax* sp. populations. Group 3 exhibited strong positive correlations, reflecting a balanced growth strategy where increases in shell length and width align proportionally with weight gain. This indicates optimal resource allocation for structural development and metabolic processes. Conversely, the weaker correlations in Group 1 suggest inconsistent growth, likely due to resource limitations or environmental stressors hindering uniform shell development.

Species diversity and environmental influences

The *Donax* sp. species richness and group size are influenced by environmental conditions, particularly dissolved oxygen levels, which support greater diversity and abundance in intertidal habitats.[16] The stronger correlations in Group 3 may reflect favorable habitat conditions, such as nutrient-rich, sheltered environments conducive to synchronized growth across shell dimensions and weight. In contrast, the weaker correlations observed in Group 1 and Group 2 may stem from dynamic or disturbed habitats with fluctuating salinity, sediment loads, or hydrodynamic forces, which disrupt uniform growth patterns.

Feeding strategies and resource utilization

Differences in group size can be attributed to feeding strategies that reduce interspecific competition. Stable isotope studies highlight variations in carbon and nitrogen ratios among species, reflecting distinct food sources and feeding behaviours, while *Donax* sp. morphology (e.g., gill and palp sizes) aligns with ecological roles and feeding modes.[17,20] The observed negative correlations of shell height with weight in Group 1 and Group 2 suggest that height is a less adaptive trait under specific ecological conditions. While shell height may enhance burrowing efficiency in certain substrates, it contributes minimally to biomass accumulation. This aligns with ecological theories positing that shell length and width are prioritized for stability, mobility, and resistance to predation in dynamic intertidal environments.

Environmental stress and population dynamics

Environmental stressors, such as eutrophication and cyanobacterial blooms, alter food availability and habitat conditions, causing fluctuations in population size, recruitment rates, and age structure.[21,22] Habitat degradation, including the decline of oyster reefs and seagrass beds, exacerbates these effects by reducing functional diversity.[1] The differences in allometric correlations across groups reflect underlying population structures. Group 3, with stronger correlations, likely comprises a more uniform population with consistent growth patterns, whereas Group 1 and Group 2 may represent populations with diverse age classes and greater genetic variability, leading to higher variation in allometric relationships. The removal of larger individuals can impair ecosystem functionality, highlighting the ecological importance of size variation within *Donax* sp. communities.[6] Therefore, the study of allometric relationships among *Donax* sp. groups reveals significant ecological insights, including growth strategies, habitat suitability, and responses to environmental stress. Stronger correlations, as seen in Group 3, reflect optimal conditions and uniform growth, while weaker relationships in Groups 1 and 2 emphasize the influence of environmental stress, resource allocation, and population dynamics. Understanding these patterns is essential for assessing the ecological roles of *Donax* sp. and the impacts of environmental changes on their populations.

Contributions to ecosystem services

Donax sp.group sizes and their associated biomass are closely tied to ecosystem services, including nutrient cycling, water filtration, and habitat structuring. Changes in *Donax* sp. abundance or group size can have cascading effects on ecosystem processes and the delivery of critical services.[2] Therefore, ecological understandings of group size differences in *Donax* sp. emphasize their critical roles in biomass production, functional diversity, and ecosystem services. These insights highlight the importance of maintaining environmental quality and conserving diverse *Donax* sp. populations to ensure the stability and resilience of marine ecosystems.

Connection between group size of donax, environmental stress, and adaptations

The relationship between group size in *Donax* sp. and their response to environmental stressors arises from complex interactions involving ecological, physiological, and evolutionary processes. Understanding these responses is critical for evaluating how *Donax* sp. populations adapt and thrive under changing environmental conditions.

Salinity and temperature stress

Salinity fluctuations and temperature changes significantly affect *Donax* sp. distribution, growth, and survival. Euryhaline species have developed osmoregulatory mechanisms to tolerate wide salinity ranges, including gene family expansions associated with solute transport and antioxidant defences.[8] Temperature variations further influence body size, with larger individuals often inhabiting colder, deeper waters to maximize energy efficiency.[23] Under stressful conditions, *Donax* sp. prioritize energy allocation for survival functions (e.g., shell repair and filtration) at the expense of uniform growth. This trade-off can weaken the relationships among shell dimensions. The strong correlations observed in Group 3 suggest reduced environmental stress, allowing optimal resource allocation for balanced growth and biomass accumulation.

Pollution and hypoxia adaptations

Donax sp. is highly sensitive to environmental pollutants, heavy metal accumulation, and hypoxia, all of which can disrupt growth patterns. Groups 1 and 2, which exhibited weaker correlations, may have faced stressors such as sediment contamination or oxygen depletion, leading to inconsistent growth across shell parameters. Pollution induces phenotypic plasticity in *Donax* sp., enhancing their ability to tolerate stress. For instance, bivalves inhabiting highly polluted areas, such as Jakarta Bay, show higher body condition indices, reflecting localized adaptations to contaminants.[5] Similarly, hypoxic conditions favour stress-tolerant populations, with selection processes enhancing their resilience in polluted environments.

Population density and habitat conditions

Bivalve population size and density are strongly influenced by habitat stability and quality. Sheltered estuarine habitats with stable salinity and nutrient availability often support dense, thriving populations.[2] In contrast, degraded or exposed habitats, such as eutrophic estuaries, limit group size due to poor water quality and reduced food availability.[7] These habitat variations likely contribute to the weaker correlations seen in Groups 1 and 2, where environmental instability may impede synchronized growth.

Adaptive mechanisms

Bivalves employ several adaptive mechanisms to cope with environmental stressors, influencing their growth patterns and group size dynamics. Under stress, they prioritize shell length and width over height to maintain stability and resist physical forces such as waves and currents, explaining the negative relationships between shell height and weight observed in Groups 1 and 2, while Group 3 likely benefits from stable conditions, enabling balanced growth. Metabolically, bivalves adjust energy usage by enhancing antioxidant defenses and producing stress proteins to combat oxidative stress caused by pollutants and temperature fluctuations.[14] Mutualistic relationships, such as those between lucinid bivalves and seagrasses, further improve resilience by mitigating sulfide toxicity and enhancing habitat quality.[24] Additionally, structural modifications in shell composition and orientation reduce drag forces, improving survival in high hydrodynamic environments.[15] Therefore, bivalve group size plays a pivotal role in maintaining critical ecosystem functions, such as sediment stabilization, nutrient cycling, and water filtration. Dense populations enhance oxygen fluxes across sediment-water interfaces, improving overall ecosystem health.[6] However, exposure to environmental stressors can reduce group size and disrupt these essential ecosystem services, emphasizing the importance of bivalve resilience and adaptive strategies.

Significance of differences in correlations among group size of bivalves from a coastal conservation perspective

The relationship between *Donax* sp. group size and their environmental interactions provides valuable insights into population dynamics, habitat requirements, and ecosystem functionality, all of which are essential for effective coastal conservation strategies.

Habitat-specific correlations

Bivalve group size often reflects specific habitat characteristics that influence growth, reproduction, and survival. For instance, *Macoma balthica* shows higher reproductive success in subtidal habitats despite lower individual efforts compared to intertidal zones.[3] Similarly, sediment composition and hydrodynamics play a key role in the spatial distribution of species like *Paphia malabarica* and *Meretrix casta*.[4] These findings underscore the importance of identifying and conserving critical habitats that support stable bivalve populations.

Environmental stressors and population dynamics

Bivalve population size and density are sensitive to environmental conditions such as salinity, temperature, and nutrient availability. Temporal fluctuations driven by rainfall, chlorophyll-α, and sea surface temperature (SST) influence biomass and recruitment success, as seen in *Spisula solida* and *Donax trunculus*.[13] Additionally, anthropogenic stressors, including heavy metal contamination, can disrupt reproductive cycles and population health, exemplified by Mytilus galloprovincialis in polluted Adriatic Sea sites.[10]

Functional diversity and ecosystem contributions

Bivalves are vital to ecosystem functioning through processes such as nutrient cycling, sediment stabilization, and water filtration. Their group size and diversity are closely linked to habitat type; for example, seagrass meadows support greater functional diversity compared to less complex habitats.[25,1] Large bivalve aggregations enhance sediment-water interface processes, significantly improving ecosystem services.[2]

Pollutant accumulation and adaptation

Variations in *Donax* sp. group size often reflect local adaptations to pollution and hypoxia. For instance, bivalves in highly impacted areas, such as Jakarta Bay, exhibit phenotypic plasticity, enabling greater tolerance to pollutants and oxygen depletion.[5] This adaptability highlights the need for monitoring pollutant accumulation in bivalve populations to evaluate ecosystem health and develop effective mitigation strategies.

Conservation and management implications

Understanding the correlations between bivalve group size and environmental factors is crucial for prioritizing conservation measures.

Marine Protected Areas (MPAs) have proven effective in maintaining bivalve populations, such as the successful conservation of Ostrea edulis in the Blackwater, Crouch, Roach, and Colne estuaries Marine Conservation Zone.[26] Additionally, restoration efforts that focus on shell budgets, habitat rehabilitation, and stress mitigation are essential for sustaining bivalve beds and their associated ecosystem functions.[27]

Conclusion

The group size of *Donax* sp. is closely linked to their adaptive responses to environmental stressors such as salinity, temperature, pollution, and habitat stability, with metabolic, physiological, and structural adaptations playing key roles in maintaining resilience. Differences in allometric correlations among three groups of *Donax* sp. from Sungai Janggut reflect varying environmental conditions, growth stages, and adaptive strategies, with Group 3 showing the strongest correlations under stable, nutrient-rich conditions, while Groups 1 and 2 exhibited weaker relationships influenced by stress or localized habitat dynamics. Factor analysis highlighted shell length and width as dominant contributors to shell weight, whereas shell height showed negative associations under stress, emphasizing the complex responses of *Donax* sp. to environmental changes. As vital bioindicators, *Donax* sp. contribute significantly to nutrient cycling, water filtration, and sediment stabilization, underscoring their ecological importance. From a conservation perspective, protecting critical habitats, mitigating anthropogenic disturbances, and monitoring *Donax* sp.growth are essential for sustaining their populations and ensuring the resilience of coastal ecosystems.

Acknowledgments

None.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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Citation: Erliana I, Bahri AAAS, Shamsir DS, et al. Allometric relationships of *Donax sp.* collected from Sungai Janggut: ecological insights, environmental stress, and coastal conservation implications. *MOJ Biol Med.* 2024;9(4):129–137. DOI: 10.15406/mojbm.2024.09.00229