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Original Article

Comparative Analysis of Morphometric Variation in the Green Mussel (*Perna viridis* Linnaeus, 1758) From Different Coastal Areas of Caraga Region, Philippines

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Abstract

Morphology often indicates genetic distinction and ecological response, mainly associated with adaptive radiation. This study aimed to determine the shell shape variation in the green mussel (*Perna viridis*) using a landmark-based approach across Barobo, Buenavista, and Cabadbaran coastal areas in the Caraga, Philippines. A total of 180 individuals, comprising 30 females and 30 males in each location, and adults of uniform size were collected. Shape variations were identified using the nine homologous anatomical landmark points through the tpsDig2 application. Symmetry, Asymmetry, and Geometric data software (SAGE) were used to analyze shape variances. Results showed statistically significant differences ($P<0.0001$) in both sexes, suggesting shell shape differences across the study areas. Further, Principal Component Analysis showed that the samples from Barobo recorded the highest Fluctuating Asymmetry (~96%), followed by Cabadbaran (~93%) and Buenavista (~92-94%) respectively. This implies that *P. viridis* populations differ significantly regarding shell shape. The morphologies of the samples from Barobo and Cabadbaran are more alike, whereas those from Buenavista are different. Frequently affected landmarks were the ligaments and posterior adductor contributing most of the Asymmetry. Moreover, ecological adaptations are essential to shaping species' morphological traits. No prior study of this kind was conducted in the Caraga region. This work presents vital information for related morphological studies on other bivalve' species. Our findings demonstrate that the samples exhibit site-specific shell shape variation, supporting its potential as a bioindicator for environmental monitoring in Philippine coastal systems. Therefore, the study emphasizes how crucial geometric morphometrics is for studying morphological variation.

Keywords: *Bivalves; Marine Ecosystem; Morphology; Northern Mindanao*

Introduction

The Green mussel (*Perna viridis*, Linnaeus, 1758) is a widely distributed bivalve species found in the Indo-Pacific region, including the coastal waters of the Philippines (Rajagopal et al., 1998; Benson et al., 2001; Soon & Ransangan, 2014; Lee *et al*., 2015). This species is known for its ecological and economic importance, a key component of local fisheries and aquaculture (Sreenivasan *et al*., 2020). *P. viridis* is commonly farmed across numerous Asian nations as a significant protein source for the

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human diet because of its superior quality and balanced nutritional profile (Wang *et al*., 2020; Saritha *et al*., 2015). Ecologically, green mussels play a vital role in maintaining marine ecosystem balance by filtering water and providing habitats for various aquatic organisms (Babarinde *et al*., 2019).

Morphological variation within *P. viridis* is influenced by both genetic and environmental factors (Smith & Taylor, 2018; Gharbi *et al*., 2010). Environmental parameters such as water temperature, salinity, and food availability significantly affect shell size and shape (Jones *et al*., 2017). Populations from different geographical locations exhibit notable differences in shell morphology, indicating local adaptation and environmental influence (Gomes *et al*., 2016). These variations are observed in shell size, shape, color, markings, and surface texture traits shaped by the interplay of hereditary elements and environmental conditions that enhance the mussels' adaptability and survival (Franza & Tanacredi, 1993). Shell variation is among the most extensively studied morphological traits. Measurements such as shell length, width, and height often exhibit considerable differences among populations, even those inhabiting geographically proximate areas (Tan & Ransangan, 2017). Environmental gradients further influence these traits: warmer waters tend to produce thinner shells, while calmer environments often yield thicker and more robust shells (Lee *et al*., 2015). Likewise, high salinity promotes elongated shells, whereas low salinity favors rounded forms (Lee, 1988). Nutrient-rich habitats support larger shell growth, while nutrient-poor conditions limit it (Cheung, 1993). Shell color ranges from deep green to brownish hues with a pearly interior, and darker pigmentation often develops under higher UV exposure as a protective response (Baker *et al*., 2007).

Mussels in polluted waters frequently display irregular coloration or rough textures due to heavy metal deposition (Cerdeira-Arias *et al*., 2024). In high-energy environments, thicker shells provide protection against strong currents and predation, while mussels in calm waters invest more energy in growth and reproduction (Babarinde *et al*., 2019).Beyond external features, internal morphological variations are also evident in the mussels from turbulent habitats often develop stronger adductor muscles to resist dislodgement (Shahabuddin *et al*., 2010), while those inhabiting nutrient-rich waters tend to possess larger gonads, reflecting higher reproductive potential (Sreenivasan *et al*., 1983). The accumulation of metals like Fe, Zn, Cu, and Mn in shellfish and gastropods can influence growth and shell development (Davies, Efekemo & Evelyn, 2022; Achudume & Odoh, 2011). Moreover, water pH, temperature, and conductivity affect the bioavailability and uptake of these metals, thereby altering shell composition and structure (Ben-Eliahu *et al*., 2020; Yap et al., 2010). Such environmental variations may drive adaptive shell morphology in *P. viridis*, with mussels from high-salinity areas tending to develop thicker and more elongated shells than those from brackish waters (Smith & Taylor, 2018). Environmental variables such as physico-chemical parameters and heavy metal concentrations play a crucial role in shaping the shells of marine and freshwater organisms (Phuong, 2014).

Geometric morphometrics (GM), a quantitative approach for analyzing biological shape and variation, has become an essential tool for distinguishing structural differences within and among species (Lecera *et al*., 2015; Cabuga Jr *et al*., 2017; Ducos & Tabugo, 2014). Through landmark-based analyses, GM minimizes the effects of size, orientation, and position to obtain precise shape measurements (Requiron *et al*., 2010; Joseph *et al*., 2016; Goswami *et al*., 2019). This method enables an objective and statistical exploration of complex morphological traits and their associations with environmental and biological factors (Gaspar et al., 2002). While morphometry focuses on examining shape variation and the relationships among measured traits, geometric morphometrics allows for the visualization of shape transformations and generates quantitative shape variables suitable for statistical analysis (Rufino *et al*., 2021; Zelditch *et al*., 2012). Therefore, these methods enable the detailed quantification of shapes and the statistical analysis of their variations while eliminating the influence of size. GM methods enable the extraction of shape and size components while maintaining the fundamental geometric characteristics of the specimens under study. (Claude, 2008; Rohlf & Marcus, 1993; Zelditch *et al*., 2012). These methods have been successfully utilized across various disciplines, including biology, ecology, evolution, ontogeny, taxonomy, and fisheries (Gold *et al*., 2014; Hedrick & Dodson, 2013; Marquez *et al*., 2010). Nonetheless, GM techniques are increasingly becoming a standard method for examining patterns of shell shape variation in bivalves (Morais *et al*., 2014; Rufino *et al*., 2023; Uba, 2021).

The Caraga Region, characterized by diverse coastal environments with varying salinity levels and water quality, may drive morphological differentiation in green mussel populations. This region hosts a diverse population of bivalves, making it a crucial area for studying their morphology and the impact of environmental factors on their populations. However, no prior study has examined the morphological variation of *P. viridis* in the region. Thus, this study aimed to analyze the shell shape variation from selected coastal areas in Caraga, Philippines, to provide insights into population structure and adaptive responses to local environmental conditions.

Materials and Methods

Study Areas

The sampling areas included the coastal waters of Cabadbaran City and Buenavista in Agusan del Norte and the Municipality of Barobo in Surigao del Sur, all located within the Caraga Region, Philippines (Figure 1). These areas were strategically chosen due to their ecological significance, accessibility, and the observed abundance of target species. The coastal zones in these localities are characterized by productive nearshore habitats such as mangroves, seagrass beds, and coral reef ecosystems that support diverse aquatic fauna. Moreover, these areas represent varying environmental conditions and anthropogenic influences, comprehensively representing the region's coastal biodiversity. Selecting multiple sites across different coastal provinces allows for a comparative assessment of species distribution and morphological variation concerning local ecological factors.

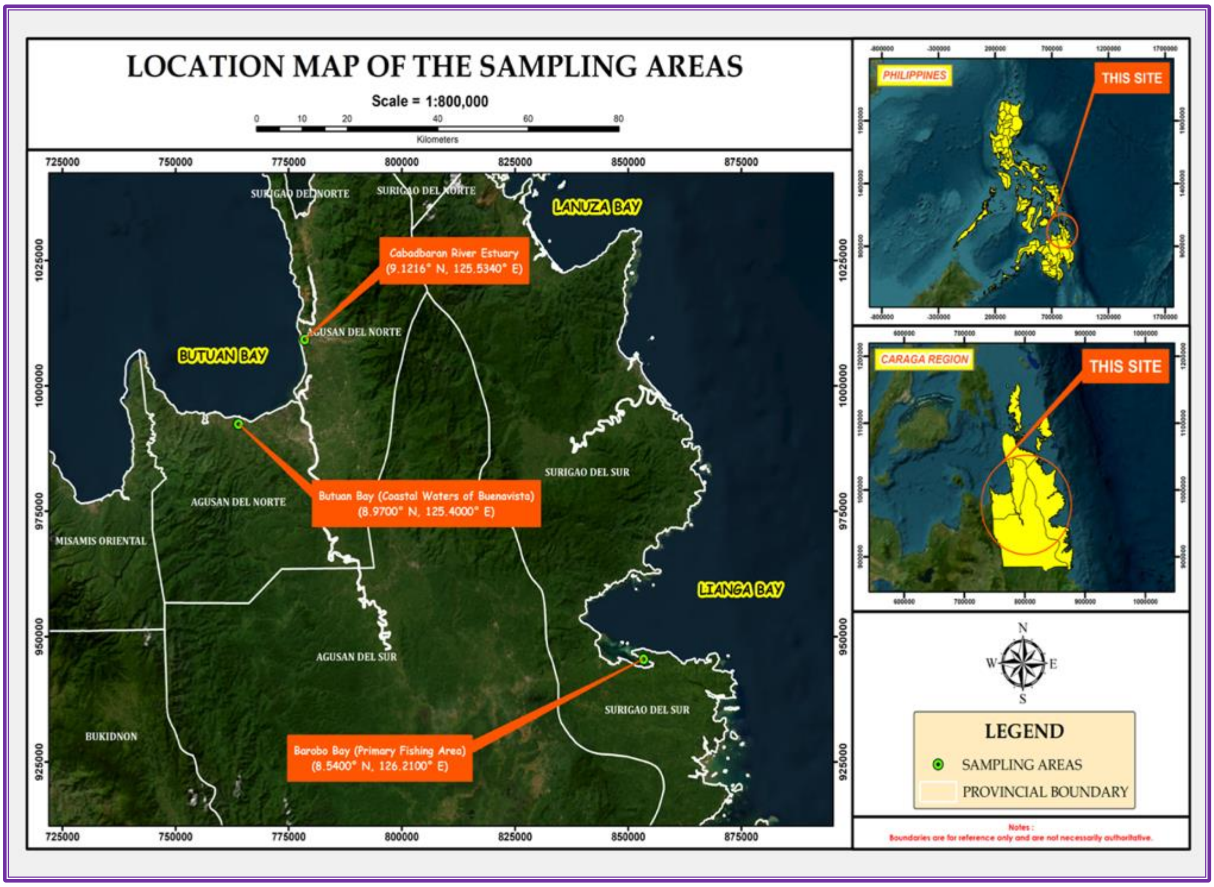


Figure 1: *Location Map of the Three Coastal Areas in Caraga Region, Philippines*.

Bivalves Collection and Processing

The collection of *P. viridis* was done by local fishermen in the three selected areas of Cabadbaran City, Buenavista in Agusan del Norte, and Barobo in Surigao del Sur. One Hundred Eighty shells of adult bivalves were collected uniformly across the sampling areas. In each study area, there are thirty males and thirty females. The shell underwent preparatory procedures, including boiling in water and washing under running water while the flesh was removed using forceps. Subsequently, corroded and cracked shells were not included (Mahilum & Demayo, 2014). Afterward, male and female samples were determined through their genitalia. By classification, males are distinct in milky to creamy white. The females are yellow orange to dark orange (Arshad, 2012). Subsequently, each sample was positioned ventrally along its left and right sides, preceded by a ruler at the bottom to establish the distance at which a digital camera was used to photograph.

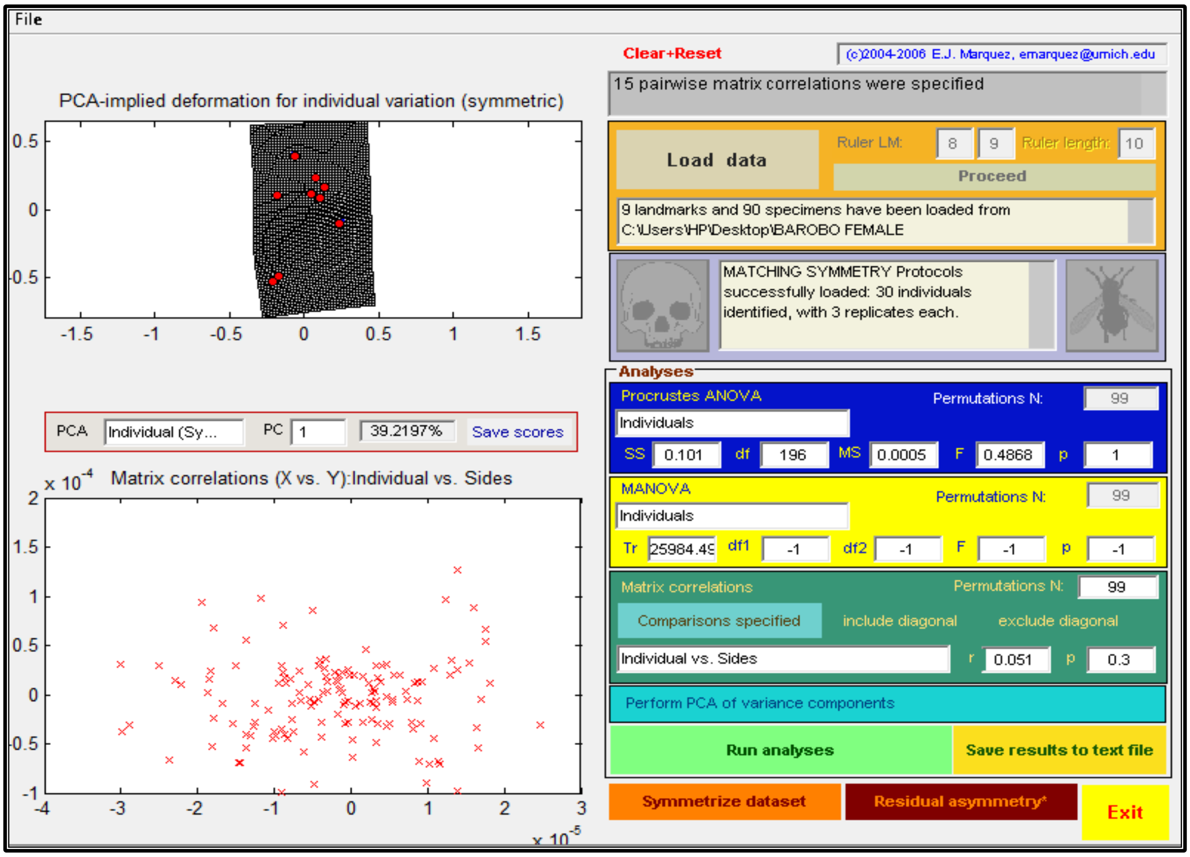
Landmark Selection and Digitization

The acquired photos were sorted by sex and then converted by using the tps file format. The samples were digitalized (Figure 2) using the tpsDig version 2 for landmarking process (Adams, Rohlf & Slice 2004). In this study, an adopted (Villaluz *et al*., 2016) nine anatomical landmark locations in the shell of *P. viridis* were presented (1- Umbo, 2-Ligament, 3- Posterior Adductor (1), 4- Posterior Adductor (2), 5- Posterior Adductor (3), 6- Posterior Adductor (4), 7- Posterior Adductor border, 8- Projection Adductor, and 9- Anterior Adductor. These landmarks have been widely used in bivalve morphometrics because they capture major functional and structural shell features.

***Figure 2**: Digitized Sample of P. viridis with Nine Homologous Anatomical Landmark Points*

Shape Analysis

The samples were analyzed in triplicate to minimize measurement error, and both the left and right shell sides were photographed for analysis. Procrustes ANOVA was employed to assess variations in bivalve shell shape, considering the factors: Individuals, Sides, and Individual × Sides as the basis of the analysis. The level of significance was evaluated at $p < 0.0001$. Principal Component Analysis (PCA) was also conducted to examine directional asymmetry and side differences. Additionally, the percentage of fluctuating asymmetry (FA) in male and female samples was compared. All landmark coordinate data were processed using the Symmetry and Asymmetry in Geometric Data (SAGE) software version 1.04 (Márquez et al., 2018) (Figure 3).



(c)2004-2006 E.J. Marquez, emarquez@umich.edu

15 pairwise matrix correlations were specified

Ruler LM: 8 9 Ruler length: 10

9 landmarks and 90 specimens have been loaded from C:\Users\HP\Desktop\BAROBO FEMALE

MATCHING SYMMETRY Protocols successfully loaded: 30 individuals identified, with 3 replicates each.

PCA: Individual (Sy... PC: 1 39.2197%

Procrustes ANOVA — Permutations N: 99 — Individuals — SS 0.101, df 196, MS 0.0005, F 0.4868, p 1

MANOVA — Permutations N: 99 — Individuals — Tr 25984.49, df1 -1, df2 -1, F -1, p -1

Matrix correlations — Permutations N: 99 — Individual vs. Sides — r 0.051, p 0.3

***Figure 3**: Symmetry and Asymmetry in Geometric Data Software Application (SAGE).*

Results

Fluctuating Asymmetry

***Table 1**: Procrustes ANOVA on the Shell Shape of P. viridis in Barobo, Surigao del Sur, Philippines*

Factors	**SS**	**DF**	**MS**	**F**	**P-value**
			Female		
Individuals	0.101	196	0.0005	0.4868	1.0000
Sides	0.0105	14	0.0008	0.7117	0.7613
Individual x Sides	0.2075	196	0.0011	75.7855	0.0001
Measurement error	0.0017	840	0	–	–
			Male		
Individuals	0.01131	196	0.0006	0.7701	0.9659
Sides	0.0102	14	0.0007	0.9746	0.4807
Individual x Sides	0.1469	196	0.0007	32.1289	0.0001
Measurement error	0.0196	840	0	–	–

Presented the Procrustes ANOVA (Table 1), the results of *P. viridis* samples collected from Barobo, Surigao del Sur, Philippines. In females, no significant morphological variation was found among individuals (p=1.000), and no directional asymmetry was observed between sides (p=0.7613). However, the interaction between individuals and sides (p = <0.0001) revealed significant fluctuating asymmetry, indicating random deviations between the left and right sides. A similar pattern was found in males, with no significant variation among individuals (p = 0.9659) and no directional asymmetry (p = 0.4807), but significant fluctuating asymmetry (p = <0.0001). This suggests that male and female mussels experience comparable developmental variability resulting in fluctuating asymmetry. A comparable pattern was observed in samples from Buenavista, Agusan del Norte. In females, there was no significant variation among individuals (p=1.000) and no directional asymmetry (p=0.1087), but significant fluctuating asymmetry (p=<0.0001) was present. In males, individual variation (p 0.9999) and sides (p = 0.0005) were not significant, but fluctuating asymmetry (p = <0.0001) again indicated random deviations likely caused by developmental instability (Table 2).

Table 2: *Procrustes ANOVA on the shell shape of P. viridis in Buenavista, Agusan Del Norte, Philippines*

Factors	**SS**	**DF**	**MS**	**F**	**P-value**
			Female		
Individuals	0.065	196	0.0003	0.5513	1.0000
Sides	0.0128	14	0.0009	1.5138	0.1087
Individual x Sides	0.118	196	0.0006	46.6131	0.0001
Measurement Error	0.010	840	0	–	–
			Male		
Individuals	0.089	196	0.000	0.5871	0.9999
Sides	0.0317	14	0.0023	1.4193	0.0005
Individual x Sides	0.01516	196	0.0008	2.9278	0.0001*
Measurement error	0.0139	840	0	–	–

Likewise, in Cabadbaran City, Agusan del Norte (Table 3), female samples showed no significant variation among individuals (p= 0.9037) and no directional asymmetry (p=0.2105) but exhibited significant fluctuating asymmetry (p= <0.0001). Male samples also showed no individual variation (p=0.9445) or directional asymmetry (p=0.0381), but fluctuating asymmetry (p = <0.0001) was again evident. These results consistently demonstrate that fluctuating asymmetry occurs in both sexes across all sampling sites.

Table 3: *Procrustes ANOVA on the shell shape of P. viridis in Cabadbaran City, Agusan Del Norte, Philippines*

Factors	**SS**	**DF**	**MS**	**F**	**P-value**
			Female		
Individuals	0.0946	196	0.0005	0.8299	0.9037
Sides	0.0106	14	0.0008	1.2992	0.2105
Individual x Sides	0.114	196	0.0006	51.211	0.0001*
Measurement error	0.0095	840	0	–	–
			Male		
Individuals	0.0877	196	0.0004	0.7959	0.9445
Sides	0.0085	14	0.006	1.0758	0.3817
Individual x Sides	0.1102	196	0.0006	37.7466	0.0001*
Measurement error	0.0125	840	0	–	–

Principal Component Analysis

The Principal Component Analysis (PCA) in Barobo samples is employed as a dimensionality reduction technique to summarize and highlight the significant patterns of shape variation *in P. viridis* shell morphology (Table 4). In females, PC1 (39%) and PC2 (24%) captured most of the variance, with landmarks at the ligament and posterior adductor contributing most to asymmetry. Further, the total variation accounts for (92%) of shape dissimilarity and (96%) of interaction/Fluctuating Asymmetry, showing that the female samples have significant shell shape differences. On the other hand, male samples PC1 (73%) and PC2 (17%) also captured most of the variance, with landmarks at the ligament and posterior adductor contributing most to asymmetry. The total variation accounting to (101%) with (96%) of interaction/FA, demonstrating that most shape variation and asymmetry in males is concentrated in fewer components, especially PC1 and PC2.

***Table 4**: Principal Component Scores Showing the Values of Symmetry and Asymmetry Scores with The Summary of the Affected Landmarks In P.Viridis from Barobo, Surigao, Del Sur*

PCA	**Individuals**	**Sides**	**Interactions** (Fluctuating Asymmetry)	**Affected Landmarks**
		Female		
PC1	39.22%		67.55%	2,4,7, and 9
PC2	23.78%		14.19%	1,2,7, and 8
PC3	13.12%		6.09%	2
PC4	10.75%	100%	4.91%	4,5, and 7
PC5	5.00%		3.60%	7 and 8
Total	**91.87%**		**96.34%**	
		Male		
PC1	72.79%		56.79%	1 and 2
PC2	17.43%	100%	21.84%	1, 2, 7, 8, and 9
PC3	10.84%		9.77%	9
Total	**101.06%**		**95.82%**	

In Buenavista females, PC1 (42%) and PC2 (20%) captured most of the variance, with landmarks at the ligament and posterior adductor contributing most to asymmetry. While the total variation accounting to (89%) and the interaction/FA (92%). In males, PC1 (42%) and PC2 (30%) also captured most of the variance, with landmarks at the ligament and posterior adductor contributing most to asymmetry. The total variation accounting to (89%) and the total interactions/FA (94%) (Table 5). Moreover, in Cabadbaran, females PC1 (51%) and PC2 (19%) captured most of the variance, with landmarks at the ligament and posterior adductor contributing most to asymmetry. The total variation accounts for (90%), and the total interactions/FA (94%). In males, PC1 (55%) and PC2 (19%) also captured most of the variance, with landmarks at the ligament and posterior adductor contributing most to asymmetry. The total variation accounts for (91%) and the total interactions/FA (93%) (Table 6).

***Table 5**: Principal Component Scores Showing the Values of Symmetry and Asymmetry Scores with The Summary of the Affected Landmarks In P.Viridis from Buenavista, Agusan Del Norte, Philippines*

PCA	**Individual**	**Sides**	**Interactions** (Fluctuating Asymmetry)	**Affected Landmarks**
		Female		
PC1	41.61%		47.95%	2,7, and 8
PC2	19.69%		24.07%	2
PC3	13.34%	100%	12.16%	2, 3, and 8
PC4	9.338%		6.26%	7 and 8
PC5	5.928%		2.81%	8
Total	89.92%		**92.38%**	
		Male		
PC1	41.69%		43.79%	2, 6, and 9
PC2	30.32%		27.02%	4, 7, and 8
PC3	9.72%	100%	10.90%	4 and 8
PC4	7.51%		8.73%	7 and 8
Total	**89.24%**		**94.44%**	

***Table 6**: Principal Component Scores Showing the Values of Symmetry and Asymmetry Scores with the Summary of the Affected Landmarks In P.Viridis from Cabadbaran City, Agusan Del Norte, Philippines*

PCA	Individuals	Sides	Interactions (Fluctuating Asymmetry)	Affected Landmarks
		Female		
PC1	36.54%		51.02%	1, 2, and 7
PC2	23.28%		18.17%	2 and 7
PC3	14.96%		11.83%	2
PC4	10.22%	100%	7.8%	3 and 8
PC5	5.26%		5.11%	
Total	**90.25%**		**93.93%**	
		Male		
PC1	54.50%		57.78%	1,2, and 9
PC2	18.92%		19.22%	7 and 8
PC3	10.09%	100%	10.35%	2 and 8
PC4	7.00%		6.08%	
Total	**90.51%**		**93.41%**	

The recurring affected landmarks 2 (Ligament), 7 (Posterior Adductor Border), 8 (Posterior Adductor) across sexes and locations point to consistent areas of the shell that are developmentally sensitive, particularly the anterior and ventral regions, which are often the most plastic in response to environmental variation. High degrees of fluctuating asymmetry demonstrate that ecological stress and individual-level factors significantly impact *P. viridis* shell shape variation. The consistent impact on specific shell landmarks, especially in regions responsible for structural and protective functions, supports the idea that shell morphology can serve as a sensitive biomonitoring tool. Subsequently, both sexes' high percentages of fluctuating asymmetry (~94%) provide compelling evidence of developmental variability. Repeated involvement of landmarks 2, 7, and 8 suggests that specific shell regions are susceptible to environmental variation, making them reliable stress indicators. Furthermore, the observable FA in male and female specimens indicates possible long-term morphological adaptation to consistent physical forces in the local habitat, such as current direction, wave exposure, or substrate type.

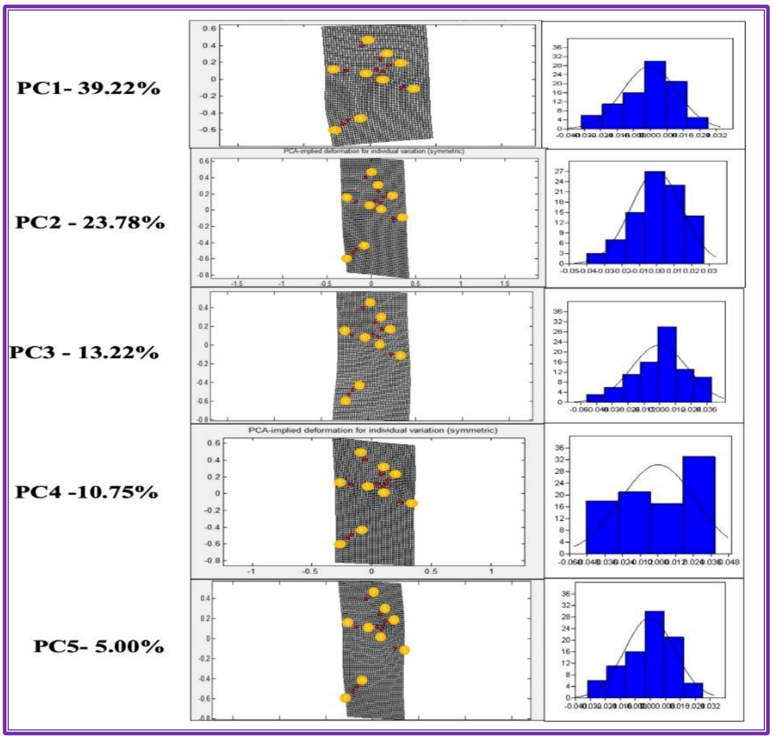


***Figure 4:** PCA-implied Deformation Plots of Female P. Viridis from Barobo, Surigao Del Sur Showing Major Landmarks Contributing to Asymmetry*

This PCA-based morphometric analysis highlights the complex interplay between developmental plasticity, environmental stress, and morphological adaptation in *P. viridis* populations from the Caraga Region. Generally, the percentage of FA and affected landmarks interactions varies across the three sampling sites. Barobo has a total FA of (96%) for females and (96%) for males (Figures 4 & 5). Followed by Buenavista has a total FA of (92%) for females and (94%) for males (Figures 6 & 7). Cabadbaran samples have a total FA of (94%) for females and (93%) for males (Figures 8 & 9). Across the three coastal areas, Barobo was the highest, followed by Cabadbaran and Buenavista respectively. This suggests that geographic location highly influences the trait differentiation of the species, if morphology reflects where the organisms inhabit.

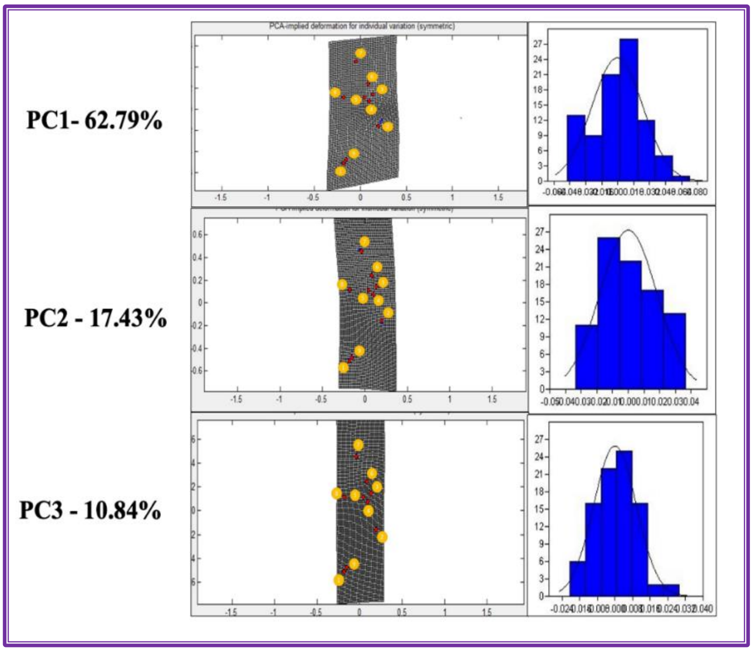


Figure 5: *PCA-Implied Deformation Plots of Male P. Viridis from Barobo, Surigao Del Sur Showing Major Landmarks Contributing to Asymmetry*

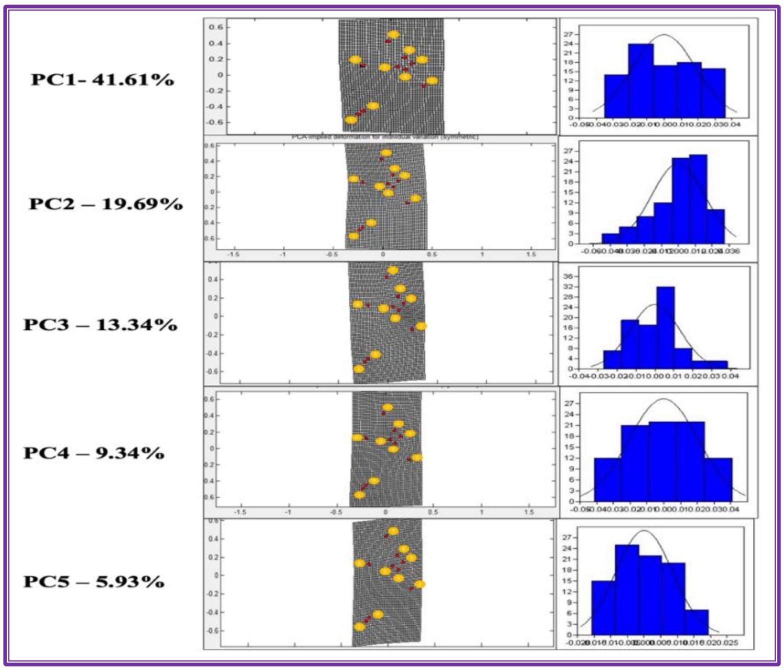


Figure 6: *PCA-Implied Deformation Plots of Female P. Viridis from Buenavista, Agusan Del Norte Showing Major Landmarks Contributing to Asymmetry*

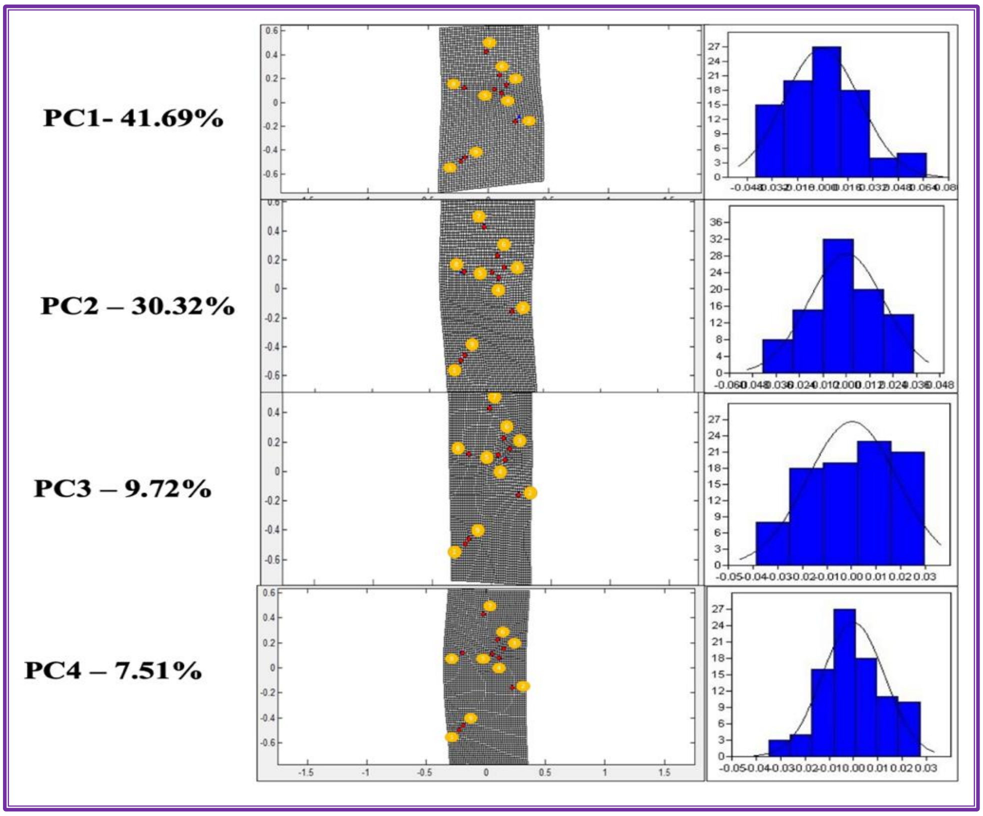


Figure 7: *PCA-Implied Deformation Plots of Male P. Viridis from Buenavista, Agusan Del Norte Showing Major Landmarks Contributing to Asymmetry*

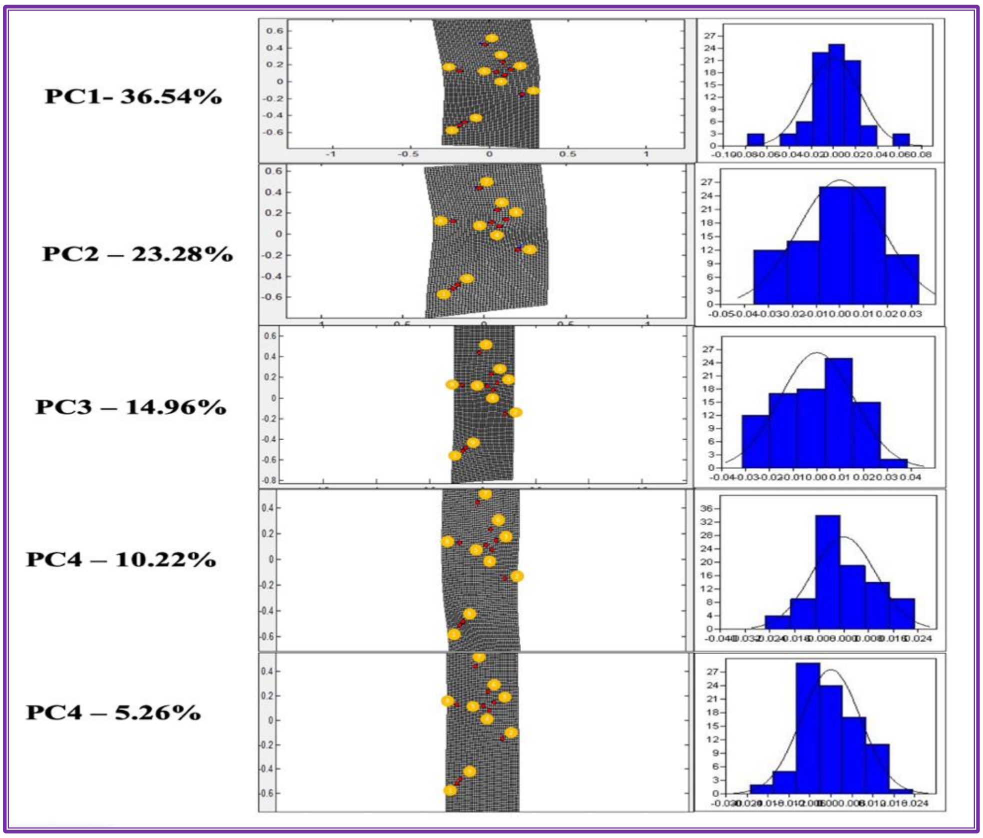


Figure 8: *PCA-Implied Deformation Plots of Female P. Viridis from Cabadbaran, Agusan Del Norte Showing Major Landmarks Contributing to Asymmetry.*

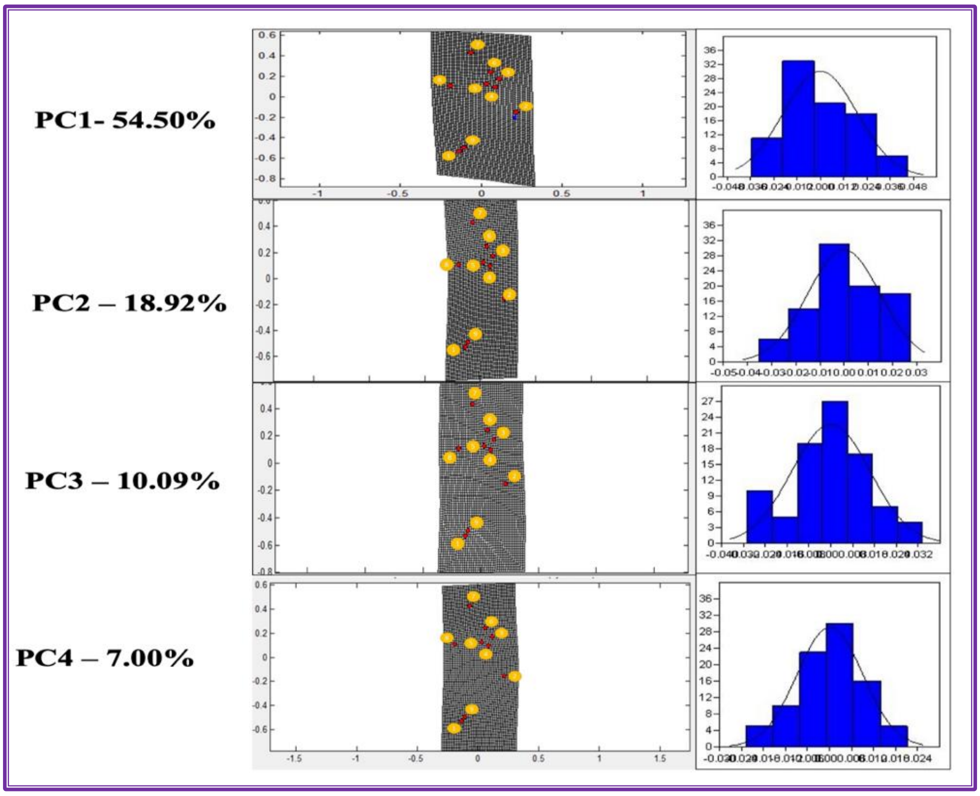


Figure 9: *PCA-Implied Deformation Plots of Male P. Viridis from Cabadbaran, Agusan Del Norte Showing Major Landmarks Contributing to Asymmetry*

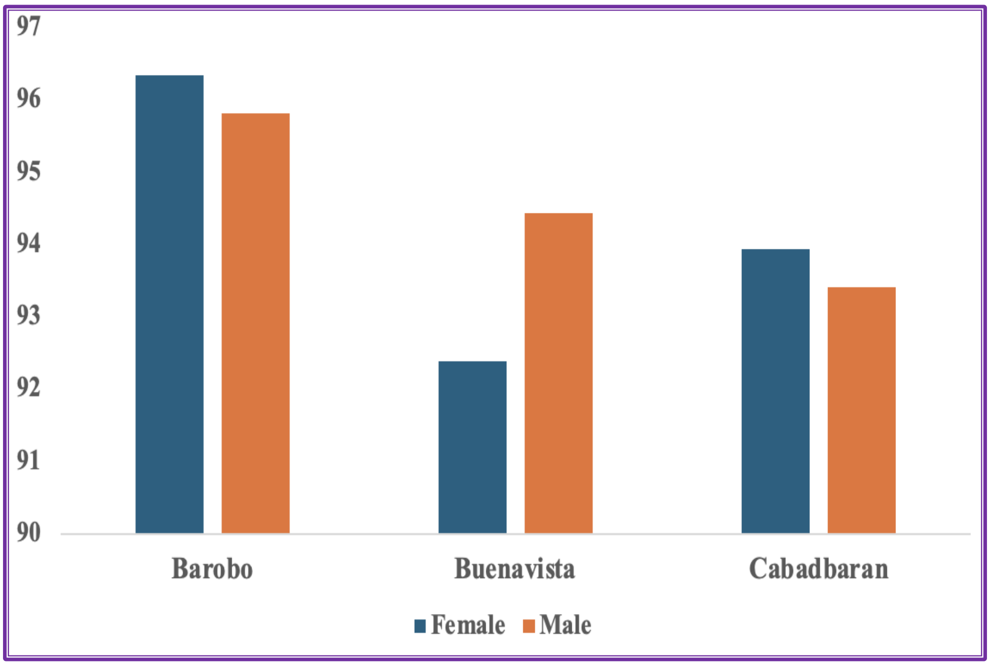


Figure 10: *Frequency Distribution Showing the Shell Shape Variation in the Appended Left/Right Region Between Sexes of P. Viridis Across Three Coastal Areas in Caraga Region, Philippines*

Additionally, (Figure 10) compares the total Fluctuating Asymmetry (FA) percentages for females and males collected at the three selected coastal areas in the Caraga Region. All FA values exceed (92%), indicating substantial random left-right shell-shaped deviations at every site. In geometric-morphometric studies, FA of this magnitude is widely accepted as a biomarker of environmental stress possibly linked to various anthropogenic resources, i.e., water contamination and heavy metal-laden sediments.

Barobo exhibits the highest FA for both sexes, mirroring earlier morphometric results that singled out this locality for the most pronounced asymmetry. Buenavista shows the lowest FA in females and a moderate level in males, suggesting comparatively reduced stress. Cabadbaran holds an intermediate position for both sexes. Sex-specific sensitivity varies by site; at Barobo and Cabadbaran, females display slightly higher FA than males, implying greater developmental sensitivity or a higher energetic cost of reproduction under stress. At Buenavista, the pattern flips; males show the greater FA, hinting that sex-specific physiological responses (e.g., growth rates, metabolic allocation) interact with a milder stress regime.

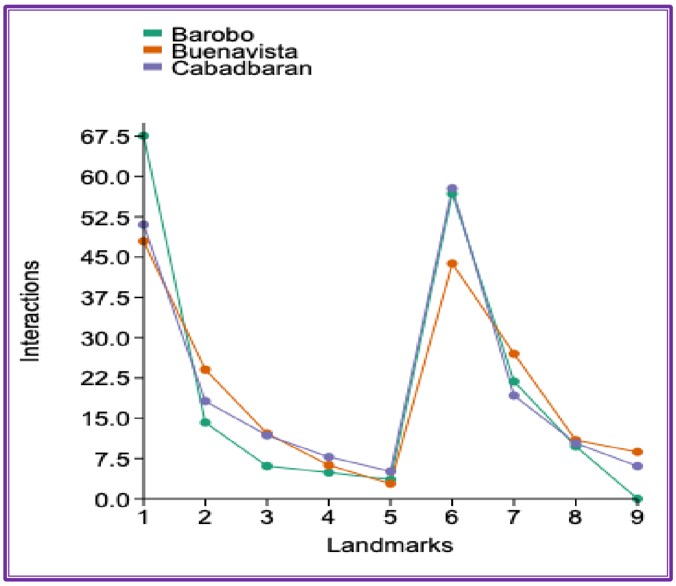


Figure 11. *Scatter Plot Showing the Interaction Frequences Across the Three Areas and Nine Anatomical Landmarks of P. Viridis Sampled from the Three Coastal Areas of Caraga Region, Philippines*

Presented in (Figure 11) is a landmark-based shape variation profile for *P. viridis* across three coastal areas: Barobo (green), Buenavista (orange), and Cabadbaran (purple). Each point on the X-axis (1–9) represents the anatomical landmark on the shell. At the same time, the Y-axis denotes the shape variation of the PCA from the scores of interactions. Landmark 1 (Umbo) has the highest variation, while all three locations show maximum shell shape variation at landmark 1. Further, Barobo registered the highest peak (~68%), and Cabadbaran and Buenavista. Landmark 1(Umbo) is typically the anterior or umbonal region of the shell, which is a critical growth point. The higher variability suggests developmental instability or adaptive changes influenced by local conditions. The landmarks 2 to 5 have a minimal variation and are relatively low and stable across all sites, suggesting morphological consistency in these mid-shell regions. These areas may be less sensitive to environmental factors or represent structurally constrained regions. Landmark 6 (Posterior Adductor), the secondary peak, a pronounced increase in variation occurs again at landmark 6 for all, especially Barobo and Cabadbaran, indicating a sensitive region of shell expansion, possibly at the posterior–ventral margin. Buenavista shows moderately less variation here, implying potentially more stable environmental conditions or reduced stress at that location. Landmarks 7 to 9 show a decline in variation; after landmark 6, a steady decrease in variation is observed from landmarks 7 to 9. On the other hand, Barobo drops to zero at landmark 9, suggesting possible structural tapering or consistency at the shell's posterior end.

The differences in landmark variation patterns among Barobo, Buenavista, and Cabadbaran reflect geographically influenced morphological plasticity. Barobo shows the most extreme variations (Landmarks 1 and 6), which aligns with prior findings of higher fluctuating asymmetry. This suggests that Barobo samples experience the highest environmental stress and temperature fluctuations. The higher FA values in Barobo may reflect greater environmental stress, possibly linked to higher anthropogenic and sediment variation in this site. Buenavista displays moderate and more balanced variation across all landmarks, indicating relatively stable environmental conditions. Cabadbaran presents an intermediate profile, with shape variation peaks close to Barobo but without as much fluctuation at the posterior end. This supports its classification as a transitional environment in terms of both stress and stability. This landmark-based shell shape analysis suggests that *P. viridis* displays site-specific morphological differences likely driven by environmental stress gradients. The most affected landmarks, particularly 1 and 6, should be monitored as morphometric indicators of ecological health and mussel developmental stress.

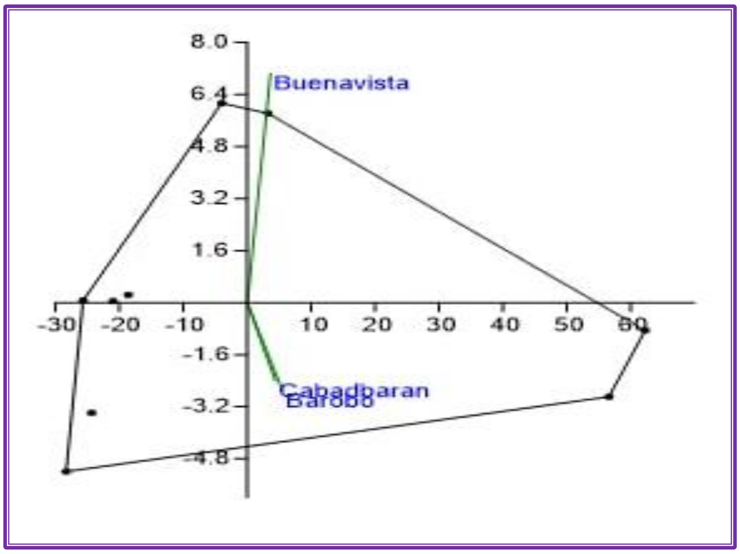


***Figure 12:** Canonical Variate Analysis of the Implied Deformation of the P. Viridis Shell Shape Across Three Coastal Areas in Caraga Region, Philippines*

The Canonical Variate Analysis (Figure 12) showed the implied deformation across the three coastal areas. It was observed that Buenavista was positioned on the Y-axis and near the center on the X-axis. This suggests that the samples from the area have a distinct shell shape compared to the other two (Barobo and Cabadbaran), especially along the Y-axis shape dimension. The Cabadbaran and Barobo areas are in the lower part of the plot, suggesting these two share similar shell shape characteristics or at least are more identical to each other than Buenavista. They cluster close together, indicating less morphological divergence between them. The green lines represent the Procrustes distance, showing the morphological distance between group means. The longer the lines, the greater the shape differences. At the same time, the Buenavista coastal area shows the most significant divergence from the others. Generally, this plot suggests a significant shell shape variation among *P. viridis* populations from different locations. The samples from Buenavista have a distinct morphology, while Cabadbaran and Barobo are more similar. These differences may reflect environmental, genetic, or ecological influences such as water quality, substrate type, or local adaptation. Taxonomic characteristics have a higher potential in delineating shape variances, while quantitative analysis objectively provides morphological characters.

Discussions

Fluctuating Asymmetry

The findings indicate a discernible variation in shell shape within the *Perna viridis* population and among the different geographical areas studied. Overall, among the analyzed factors, Individuals, Sides, and Individuals × Sides, only the interaction (Individuals × Sides) was statistically significant (p= <0.0001), indicating morphological shape variation associated with developmental disparity. This may suggest that *P. viridis* broad tolerance to environmental fluctuations in coastal ecosystems (Gamier *et al*., 2019). Environmental factors such as trophic conditions, population density, wave impact, and water depth influence shell shape (Seed, 1980; Yonge & Campbell, 1968). Mussel density and growth rate can significantly affect shell morphology, with densely packed populations producing elongated shells due to physical constraints, while sparsely distributed individuals develop taller, more triangular forms (Seed, 1968; Caill-Milly *et al*., 2012). Shell shape variation also corresponds with population age structure and habitat conditions. Sites with fewer predators and older populations tend to harbor mussels with distinctive, hoof-like shells (Orton, 1928; Negus, 1966), whereas areas dominated by younger individuals show less pronounced morphological development (Sivalingam, 1997). Such variability underscores the role of growth rate, crowding, and local environmental pressures in shaping shell morphology (Gharbi *et al*., 2010). Because environmental conditions fluctuate spatially and temporally, significant shape differences may arise among individuals within the same locality (Costa et al., 2008). Previous studies further suggest that shell shape differences are largely due to phenotypic plasticity mussels tend to develop morphologies characteristic of their current environment regardless of origin (Gosling, 2003). Bivalve shell morphology and growth are regulated by a combination of abiotic (exogenous) and biotic (endogenous) influences (Gaspar *et al*., 2002).

Various environmental factors have been shown to influence shell morphology and relative proportions in many bivalve species. These include latitude (Beukema & Meehan, 1985), depth (Claxton et al., 1998), shore level (Franz, 1993), tidal level (Dame, 1972), currents (Fuiman *et al*., 1999), water turbulence (Hinch & Bailey, 1988), wave exposure (Akester & Martel, 2000), substrate type (Claxton *et al*., 1998), and sediment composition (Newell & Hidu, 1982). Moreover, burrowing behavior, efficiency, and capability have also been reported to affect bivalve species' relative growth and shape development (Eagar, 1978; Seed, 1980). Morphological traits such as shell size and shape influence biomechanics, physiology, reproductive success, and overall fitness (Stanley, 1970; Gosling, 2003). The considerable diversity of shell morphology in bivalves has been attributed to adaptive evolutionary processes shaped by both biotic and abiotic factors (Lande & Arnold, 1983; Belonsky & Kennedy, 1988; Hamilton et al., 2020). Environmental variables including geographic location, depth, tides, current strength, shore level, turbulence, and substrate type all contribute to these variations (Beaukema & Meehan, 1985; Claxton *et al*., 1998; Dame, 1972; Furman et al., 1999; Franz, 1993; Akester & Martel, 2000; Bailey & Green, 1988; Eagar, 1978; Newell & Hidu, 1982). Growth rate and shell proportions can also vary seasonally and interspecifically depending on food availability, maturation, and environmental stability (Sutherland, 1970; Parry, 1978; Kay & Magruder, 1977; Branch, 1981). Hence, shell length and height remain fundamental parameters in assessing growth and morphological variation among bivalves (Franz, 1993; Zainudin & Tsuchiya, 2007).

Moreover, FA is commonly used as a bioindicator of developmental variability in bivalves and other organisms, often increasing under stress, such as pollution or environmental disturbance (Clarke, 1995; Leung & Forbes, 1997). While several studies have reported increased FA in bivalves in response to metal contamination Rodriguez *et al*., 2019; Dutta *et al*., s2022), the present study did not perform such a test. However, this study's absence of such a pattern is associated with the effective detoxification or tolerance mechanisms in *P. viridis* (Yap *et al*., 2023). Variability in other environmental factors (e.g., salinity, temperature, food availability) masks the potential effects of metal exposure (Bayen, 2012). Although *P. viridis* is known to bioaccumulate heavy metals, the link between external contamination (in sediments or water) and morphological changes is complex and context-dependent (Yap et al., 2022). Studies suggest that metal uptake and its impact on physiology and morphology vary depending on the metal speciation and bioavailability (Rainbow, 2002). Exposure duration, organism age (Wong *et al*., 2000), and local hydrodynamic and sedimentation processes (Bayen, 2012). In addition, shell growth and morphology are influenced by multiple environmental drivers, not just pollution. For example, temperature, salinity, and nutrient levels significantly shape shell structure and asymmetry (Guerra-García*,* Ros & Baeza-Rojano, 2015). Similar observations have been noted in previous environmental monitoring studies where spatial heterogeneity in coastal environments led to weak statistical associations despite underlying ecological interactions (Mouneyrac *et al*., 2003). Inconsistencies in species morphometric relationships may stem from distinct hydrological and sedimentological conditions among various geographic areas (Gaspar *et al*., 2002).

Principal Component Analysis, Scatter Plot and Canonical Variate Analysis

Principal Component Analysis (PCA) is a fundamental multivariate statistical tool that summarizes and interprets complex datasets by reducing their dimensionality while retaining most of the original variation (Jolliffe & Cadima, 2016). In morphometric studies, PCA is particularly valuable because it identifies the main patterns of shape variation among individuals or populations by transforming correlated variables into a smaller set of uncorrelated variables called principal components (Rohlf & Marcus, 1993). In this study, the shell shape difference of the samples was identified, and it was supported by the study conducted by Jayalakshmy *et al*. (2013), describing that *P. viridis,* known as an amphibole species, and its growth is influenced by environmental and climatic conditions. At the same time, this mussel indicates pollution by heavy metals, organic chlorides, and petroleum hydrocarbons (Gaspar *et al*., 2002). Further, the growth characteristics of this species are essential to understand the influence of climatic conditions on their morphometry. While temperature is the main factor influencing their growth, other factors include the habitat, such as littoral, sub-littoral, and estuarine regions (Kulakovskii & Lezin, 2002). Likewise, factors such as reproduction, population density, and habitat influence tissue growth. In comparison, the study indicated that the smaller size of *P.indica* may be attributed to the different environmental conditions and the presence of predators, i.e., mussels are consumed by fishes like leatherjackets, crabs, and starfish (Jayalakshmy *et al*., 2013). Related studies also show that the influence of the biological environment intercepts the morphology due to the habitat differences (Black, 1977; Lewis & Bowman, 1975).

Study suggests that variations in the relative proportions of bivalve shells during growth are generally linked to maintaining an optimal physiological area-to-volume ratio in response to environmental conditions (Rhoads & Pamella, 1970). In several bivalve species, shell height and width increase with growth to enhance stability and prevent dislodgement by turbulence and currents (Eagar, 1978; Hinch & Bailey, 1988). Also, these ontogenetic changes in bivalves are associated with differences in lifestyle between juveniles, active burrowers, and adults, who are more sedentary and typically inhabit deeper layers of bottom sediments (Thayer, 1975). The data implied that habitat heterogeneity likely affects shell shape with the interplay of ecological components. Studies have compared the ratios of several morphometric variables in mussels (Dermott & Munawar, 1993; Pathy & Mackie, 1993). Simple allometry occurs when the ratio between the specific growth rates of two characters is constant (Blackstone, 1987). Characteristically, the growth rate of mussels may vary intra or inter-specifically depending on several factors, including tides, seasons (Urdy et al., 2010) food availability (Parry, 1978), maturation (Kay & Magruder, 1977), and eventually lead to different proportions and longevities (Branch, 1981). Multivariate analysis can identify independent characters for separating morphological forms (Dodson & Lee, 2006). The growth and shape of shells are influenced by abiotic (environmental) and biotic (physical) factors (Miguel et al., 2002). At the same time, abiotic factors include geographical location (Beukema & Meehan, 1985), depth (Claxton *et al*., 1998), shore level (Franz, 1993), tides (Dame, 1972), currents (Fuiman et al.,1999), turbulence (Bailey & Green, 1988), waves (Akester & Martel, 2000), type of bottom (Claxton *et al*., 1998), sediment texture (Newell & Hidu, 1982) and burrowing behavior (Eagar, 1978). In this study, the mussels taken from three different environments were found to vary by size and shape. Hence, other factors must also be included to identify their morphometric behavior further.

Assessing morphological changes in the green mussel is important for understanding the species adaptive responses to varying environmental conditions. Morphological variation, particularly in shell shape and size, often reflects the influence of abiotic and biotic factors such as water temperature, salinity, substrate type, and nutrient availability (Seed, 1980; Akester & Martel, 2000). These phenotypic variations can indicate environmental stress and habitat quality, providing valuable insights into ecosystem health and local adaptation processes (Claxton *et al*., 1998; Gosling, 2003).Besides, monitoring morphological variation among geographically distinct populations supports the identification of potential stock differentiation and population structure, which are essential for sustainable management and aquaculture practices (Innes & Bates, 1999; Rajagopal et al., 2006). Geometric morphometric analysis, in particular, provides a powerful approach to quantify and visualize these variations, allowing researchers to detect subtle shape differences that may be linked to environmental heterogeneity or anthropogenic impacts (Rohlf & Marcus, 1993; Zelditch *et al*., 2012). Understanding such morphological dynamics is vital for evaluating the ecological plasticity of *P. viridis* and informing conservation strategies in rapidly changing coastal ecosystems. Thus, by employing geometric morphometric techniques, the study aims to quantify and compare shape and size variations among populations, elucidating the potential influence of environmental and ecological factors on shell morphology. The findings are expected to contribute to a deeper understanding of phenotypic plasticity and population differentiation in *P. viridis* across varying coastal habitats.

Conclusion

The comparative morphometric assessment of the green mussel (*Perna viridis* Linnaeus, 1758) from various coastal areas of the Caraga Region revealed discernible spatial variations in shell shape and size, reflecting the species' morphological plasticity in response to environmental heterogeneity. Our findings demonstrate that *P. viridis* exhibits site-specific shell shape variation, supporting its potential as a bioindicator for environmental monitoring. Applying geometric morphometric techniques proved effective in quantifying and visualizing subtle morphological differences among populations, thereby providing practical evidence of potential ecological and hydrological influences on shell form. These findings emphasize the importance of integrating morphometric analyses in evaluating population structure, local adaptation, and habitat-specific responses of the species. Such insights are essential for advancing understanding of the species' ecological resilience and supporting informed management and conservation strategies within the dynamic coastal ecosystems of the Philippines.

Conflict of Interest

The authors declare no conflict of interest.

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References

Achudume, A. C., & Odoh, S. (2011). Seasonal Variations in Physico-Chemical Parameters of the Topcamp Stream and Heavy Metals Accumulation in Freshwater Crustacean. *Journal of Ecosystem & Ecography, 1*(2), 1-2.

Adams, D. C., Rohlf, F. J., & Slice, D. E. (2004). Geometric morphometrics: ten years of progress following the revolution. *Italian Journal of Zoology, 7*1(1), 5-16. https://doi.org/10.1080/11250000409356545

Akester, R. J., & Martel, A. L. (2000). Shell shape, dysodont tooth morphology, and hinge-ligament thickness in the bay mussel Mytilus trossulus correlate with wave exposure. *Canadian Journal of Zoology*, *78*(2), 240-253. https://doi.org/10.1139/cjz-78-2-240

Babarinde, S. A., Adewumi, A. A., & Olaniyi, O. O. (2019). Ecological role of bivalves in coastal ecosystems: A review. *Marine Ecology Progress Series, 621*(2), 45–59.

Bailey, R. C., & Green, R. H. (1988). Within-basin variation in the shell morphology and growth rate of a freshwater mussel. *Canadian Journal of Zoology*, *66*(7), 1704-1708. https://doi.org/10.1139/z88-246

Baker, P., Fajans, J. S., Arnold, W. S., Ingrao, D. A., Marelli, D. C., & Baker, S. M. (2007). Range and dispersal of a tropical marine invader, the Asian green mussel, Perna viridis, in subtropical waters of the southeastern United States. *Journal of Shellfish Research*, *26*(2), 345-355. https://doi.org/10.2983/0730-8000(2007)26[345:RADOAT]2.0.CO;2

Bayen, S. (2012). Occurrence, bioavailability and toxic effects of trace metals and organic contaminants in mangrove ecosystems: a review. *Environment international, 48*, 84-101. https://doi.org/10.1016/j.envint.2012.07.008

Belonsky, G. M., & Kennedy, B. W. (1988). Selection on individual phenotype and best linear unbiased predictor of breeding value in a closed swine herd. *Journal of Animal Science*, *66*(5), 1124-1131. https://doi.org/10.2527/jas1988.6651124x

Ben-Eliahu, N., Herut, B., Rahav, E., & Abramovich, S. (2020). Shell growth of large benthic foraminifera under heavy metals pollution: implications for geochemical monitoring of coastal environments. *International Journal of Environmental Research and Public Health, 17*(10), 3741. https://doi.org/10.3390/ijerph17103741

Benson, A. J., Marelli, D. C., Frischer, M. E., Danforth, J. M., & Williams, J. D. (2001). Establishment of the green mussel, Perna viridis (Linnaeus 1758) (Mollusca: Mytilidae) on the west coast of Florida. *Journal of Shellfish Research*, *20*(1), 21-29. https://pubs.usgs.gov/publication/70023673

Beukema, J. J., & Meehan, B. W. (1985). Latitudinal variation in linear growth and other shell characteristics of Macoma balthica. *Marine Biology, 90*(1), 27-33. https://doi.org/10.1007/BF00428211

Black, R. (1977). Population regulation in the intertidal limpet Patelloida alticostata (Angas, 1865). *Oecologia, 30*(1), 9-22. https://doi.org/10.1007/BF00344888

Blackstone, N. W. (1987). Size and time. Systematic Zoology, 36(2), 211-215. https://doi.org/10.2307/2413271

Branch, G.M. (1981). The biology of limpets: physical factors, energy flow and ecological interactions. *Oceanography Marine Biology Annual Review. 19*, 235-380. https://cir.nii.ac.jp/crid/1574231875108030464

Cabuga Jr, C.C., Apostado, R.R.Q., Abelada, J. Z., Calagui, L.B., Presilda, C.J., Angco, M.K.A., Bual, J.L., Lador, J.E.O., Jumawan, J.H., Jumawan, J.C., Havana, H.C., Requieron, E.A., Torres, M.A. J. (2017). Comparative fluctuating asymmetry of spotted barb (*Puntius binotatus*) sampled from the Rivers of Wawa and Tubay, Mindanao, Philippines. *Computational Ecology and Software,* *7*(1), 8-27. http://www.iaees.org/publications/journals/ces/articles/2017-7(1)/fluctuating-asymmetry-of-spotted-barb.pdf

Caill-Milly, N., Bru, N., Mahé, K., Borie, C., & D′ Amico, F. (2012). Shell shape analysis and spatial allometry patterns of Manila clam (Ruditapes philippinarum) in a mesotidal coastal lagoon. *Journal of Marine Sciences*, *2012*(1), 281206. https://doi.org/10.1155/2012/281206

Cerdeira-Arias, J. D., Otero, J., Barceló, E., Del Río, G., Freire, A., García, M., ... & Álvarez-Salgado, X. A. (2024). Environmental effects on abundance and size of harvested bivalve populations in intertidal shellfish grounds. *Marine Environmental Research*, *202*, 106808. https://doi.org/10.1016/j.marenvres.2024.106808

Cheung, S. G. (1993). Population dynamics and energy budgets of green-lipped mussel Perna viridis (Linnaeus) in a polluted harbour. *Journal of Experimental Marine Biology and Ecology*, *168*(1), 1-24. https://doi.org/10.1016/0022-0981(93)90113-3

Claude, J. (2008). Morphometrics with R. Springer Science & Business Media.

Claxton, W. T., Wilson, A. B., Mackie, G. L., & Boulding, E. G. (1998). A genetic and morphological comparison of shallow-and deep-water populations of the introduced dreissenid bivalve Dreissena bugensis. *Canadian Journal of Zoology*, *76*(7), 1269-1276. https://doi.org/10.1139/cjz-76-7-1269

Costa, C., Aguzzi, J., Menesatti, P., Antonucci, F., Rimatori, V., & Mattoccia, L. M. (2008). Shape analysis of different populations of clams in relation to their geographical structure. *Journal of Zoology*, *276*(1), 71-80. https://doi.org/10.1111/j.1469-7998.2008.00469.x?urlappend=%3Futm_source%3Dresearchgate

Dame, R. F. (1972). Comparison of various allometric relationships in intertidal and subtidal American oysters. *Fish Bull*, *70*(4), 1121-1126. https://spo.nmfs.noaa.gov/sites/default/files/pdf-content/1972/704/dame.pdf

Davies, I. C., Efekemo, O., & Evelyn, G. A. (2022). Quantal response and histopathological effects of sub-lethal concentrations of a selected oilfield chemical on African Catfish (*Clarias gariepinus*). *Journal Biology and Genetic Research, 8*(2), 22-41. https://doi.org/10.56201/ijssmr.v8.no1.2022.pg32.40

Dermott, R., & Munawar, M. (1993). Invasion of Lake Erie offshore sediments by Dreissena, and its ecological implications. *Canadian Journal of Fisheries and Aquatic Sciences*, *50*(11), 2298-2304. https://doi.org/10.1139/f93-254

Dodson, S. I., & Lee, C. E. (2006). Recommendations for taxonomic submissions to Hydrobiologia. *Hydrobiologia*, *556*(1), 1-5. https://doi.org/10.1007/s10750-005-5370-0

Ducos, M. B., & Tabugo, S. R. (2015). Fluctuating asymmetry as bioindicator of stress and developmental instability in Gafrarium tumidum (ribbed venus clam) from coastal areas of Iligan Bay, Mindanao, Philippines. *Aquaculture, Aquarium, Conservation & Legislation*, *8*(3), 292-300.

Dutta, J., Zaman, S., Thakur, T. K., Kaushik, S., Mitra, A., Singh, P., ... & Datta, R. (2022). Assessment of the bioaccumulation pattern of Pb, Cd, Cr and Hg in edible fishes of East kolkata Wetlands, India. *Saudi Journal of Biological Sciences, 29*(2), 758-766. https://doi.org/10.1016/j.sjbs.2021.09.039

Eagar, R. M. C. (1978). Shape and function of the shell: a comparison of some living and fossil bivalve molluscs. *Biological Reviews*, *53*(2), 169-210. https://doi.org/10.1111/j.1469-185X.1978.tb01436.x

Franz, D. R. (1993). Allometry of shell and body weight in relation to shore level in the intertidal bivalve Geukensia demissa (Bivalvia: Mytilidae). Journal of Experimental Marine Biology and Ecology, 174(2), 193-207. https://doi.org/10.1016/0022-0981(93)90017-I

Franz, D. R., & Tanacredi, J. (1993). Variability in growth and age structure among populations of ribbed mussels, Geukensia demissa (Dillwyn)(Bivalvia: Mytilidae), in Jamacia Bay, New York (Gateway NRA). *The Veliger*, *36*(3), 220-227. https://scispace.com/pdf/variability-in-growth-and-age-structure-among-populations-of-1gyz6kfv9q.pdf

Fuiman, L. A., Gage, J. D., & Lamont, P. (1999). Shell morphometry of the deep sea protobranch bivalve Ledella pustulosa in the Rockall Trough, north-east Atlantic. *Journal of the Marine Biological Association of the United Kingdom*, *79*(4), 661-671. https://doi.org/10.1017/S0025315498000824

Gamier, D. E. F., Velasco, D. A. B., Dalisay, T. M. A., & Saco, J. A. (2019). Geometric morphometric analysis on the shell of green mussel (Perna viridis) from two culturing sites in Cavite province. *International Research Journal on Innovations in Engineering, Science and Technology*, *5*, 01-04. https://ojs.batstate-u.edu.ph/index.php/IRJIEST/article/view/41.

Gaspar, M. B., Santos, M. N., Vasconcelos, P., & Monteiro, C. C. (2002). Shell morphometric relationships of the most common bivalve species (Mollusca: Bivalvia) of the Algarve coast (southern Portugal). *Hydrobiologia*, *477*(1), 73-80. https://doi.org/10.1023/A:1021009031717

Gaspar, M. B., Santos, M. N., Vasconcelos, P., & Monteiro, C. C. (2002). Shell morphometric relationships of the most common bivalve species (Mollusca: Bivalvia) of the Algarve coast (southern Portugal). *Hydrobiologia*, *477*(1), 73-80. https://doi.org/10.1023/A:1021009031717

Gharbi, A., Chatti, N., Said, K., & Van Wormhoudt, A. (2010). Genetic variation and population structure of the carpet shell clam Ruditapes decussatus along the Tunisian coast inferred from mtDNA and ITS1 sequence analysis. *Biologia*, *65*(4), 688-696. https://doi.org/10.2478/s11756-010-0069-8

Gold, M. E. L., Brochu, C. A., & Norell, M. A. (2014). An expanded combined evidence approach to the Gavialis problem using geometric morphometric data from crocodylian braincases and Eustachian systems. *PloS One*, *9*(9), e105793. https://doi.org/10.1371/journal.pone.0105793

Gomes, F., Pereira, A., & Santos, R. (2016). Geographic variation in the shell morphology of Perna viridis along the Indian coast. *Journal of Marine Biology, 45*(3), 245–258.

Gosling, E. (2003). Bivalve molluscs: Biology, ecology and culture. Blackwell Publishing Ltd, US. https://doi.org/10.1002/9780470995532?urlappend=%3Futm_source%3Dresearchgate

Goswami, A., Watanabe, A., Felice, R. N., Bardua, C., Fabre, A. C., & Polly, P. D. (2019). High-density morphometric analysis of shape and integration: the good, the bad, and the not-really-a-problem. *Integrative and comparative biology, 59*(3), 669-683. https://doi.org/10.1093/icb/icz120

Guerra-Garcia, J. M., Ros, M., & Baeza-Rojano, E. (2015). Seasonal fluctuations and dietary analysis of fouling caprellids (Crustacea: Amphipoda) from marinas of southern Spain. *Marine Biology Research, 11*(7), 703-715. https://doi.org/10.1080/17451000.2014.985231

Hamilton, A. M., Selwyn, J. D., Hamner, R. M., Johnson, H. K., Brown, T., Springer, S. K., & Bird, C. E. (2020). Biogeography of shell morphology in over-exploited shellfish reveals adaptive trade-offs on human-inhabited islands and incipient selectively driven lineage bifurcation. *Journal of Biogeography*, *47*(7), 1494-1509. https://doi.org/10.1111/jbi.13845?urlappend=%3Futm_source%3Dresearchgate

Hedrick, B. P., & Dodson, P. (2013). Lujiatun psittacosaurids: understanding individual and taphonomic variation using 3D geometric morphometrics. *PLoS One*, *8*(8), e69265.https://doi.org/10.1371/journal.pone.0069265

Hinch, S. G., & Bailey, R. C. (1988). Within-and among-lake variation in shell morphology of the freshwater clam *Elliptio complanata* (Bivalvia: Unionidae) from south-central Ontario lakes. *Hydrobiologia, 157*(1), 27-32. https://doi.org/10.1007/BF00008807

Innes, D. J., & Bates, J. A. (1999). Morphological variation of Mytilus edulis and Mytilus trossulus in eastern Newfoundland. *Marine Biology*, *133*(4), 691-699. https://www.mun.ca/biology/dinnes/Innes.pdf

Jayalakshmy, K. V., Nair, M., DileepKumar, R., & Vijayan, M. (2013). Biometric and morphometric studies of Perna viridis and Perna indica along the southwest coast of India: a statistical approach. *Journal of Experimental Biology and Agricultural Sciences,* *1*(4), 285-296. https://drs.nio.res.in/drs/bitstream/handle/2264/4392/J_Exp_Biol_Agric_Sci_1_285.pdf;jsessionid=80CB0332D5EFD15B23740ADB4E1CD3FE?sequence=1

Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: a review and recent developments. *Philosophical transactions of the royal society A: Mathematical, Physical and Engineering Sciences*, *374*(2065), 20150202. https://doi.org/10.1098/rsta.2015.0202

Jones, M. E., Smith, K. L., & Taylor, D. J. (2017). Environmental influences on shell morphology in marine bivalves. Aquatic Biology, 34(4), 213–222.

Joseph, C. C. D., Jumawan, H., Hernando, B. J., Boyles, L. Z., Jumawan, J. C., Velasco, J. P. B., ... & Torres, M. A. J. (2016). Fluctuating asymmetry in evaluating the developmental instability of Glossogobius giuris (Hamilton, 1822) from Lake Mainit, Surigao del Norte, Philippines. *Computational Ecology and Software*, *6*(2), 55.

Kay, E.A., Magruder, W. (1977). *The biology of opihi*. Department of planning and economic development, Hawai.

Kulakovskii, E. E., & Lezin, P. A. (2002). Filtration activity of the blue mussel, Mytilus edulis (Mytilida, Mytilidae), under influence of the starfish, Asterias rubens (Forcipulata, Asteriidae), *Zoologicheskii Zhurnal, 81*(3), 292–298.

Lande, R., & Arnold, S. J. (1983). The measurement of selection on correlated characters. Evolution, 37(6), 1210-1226. Oxford University Press. https://doi.org/10.2307/2408842

Lecera, J. M., Pundug, N. A., Banisil, M. A., Flamiano, R. S., Torres, M. A., Belonio, C. L., & Requieron, E. A. (2015). Fluctuating asymmetry analysis of trimac Amphilophus trimaculatus as indicator of the current ecological health condition of Lake Sebu, South Cotabato, Philippines. *Aquaculture, Aquarium, Conservation & Legislation*, *8*(4), 507-516. https://www.academia.edu/27832077/Fluctuating_asymmetry_analysis_of_trimac_Amphilophus_trimaculatus_as_indicator_of_the_current_ecological_health_condition_of_Lake_Sebu_South_Cotabato_Philippines

Lee, S. Y. (1988). The reproductive cycle and sexuality of the green mussel Perna viridis (L.)(Bivalvia: Mytilacea) in Victoria Harbour, Hong Kong. *Journal of Molluscan Studies*, *54*(3), 317-323. https://doi.org/10.1093/mollus/54.3.317

Lee, Y. C., Chou, F. C., & Wu, J. L. (2015). Distribution and population dynamics of green mussel (*Perna viridis*) in Southeast Asia. *Asian Fisheries Science, 28*(1), 67–80.

Lewis, J. R., & Bowman, R. S. (1975). Local habitat-induced variations in the population dynamics of Patella vulgata L. *Journal of experimental marine Biology and Ecology*, *17*(2), 165-203. https://doi.org/10.1016/0022-0981(75)90029-5

Mahilum, J. J. M., & Demayo, C. G. (2014). Describing lake populations of the golden apple snail, *Pomacea canaliculata* using landmark-based geometric morphometric analysis. *Journal of Entomology Zoology Studies, 2*(4), 139-144.. https://www.entomoljournal.com/vol2Issue4/pdf/55.1.pdf

Márquez, F., Adami, M. L., Trovant, B., Nieto-Vilela, R. A., & González-José, R. (2018). Allometric differences on the shell shape of two scorched mussel species along the Atlantic South American Coast. *Evolutionary Ecology*, *32*(1), 43-56. https://doi.org/10.1007/s10682-018-9928-5

Marquez, F., Robledo, J., Peñaloza, G. E., & Van der Molen, S. (2010). Use of different geometric morphometrics tools for the discrimination of phenotypic stocks of the striped clam *Ameghinomya antiqua* (Veneridae) in North Patagonia, Argentina. *Fisheries Research, 101*(1-2), 127-131. https://doi.org/10.1016/j.fishres.2009.09.018

Morais, P., Rufino, M. M., Reis, J., Dias, E., & Sousa, R. (2014). Assessing the morphological variability of Unio delphinus Spengler, 1783 (Bivalvia: Unionidae) using geometric morphometry. *Journal of Molluscan Studies*, *80*(1), 17-23. https://doi.org/10.1093/mollus/eyt037

Mouneyrac, C., Mastain, O., Amiard, J. C., Amiard-Triquet, C., Beaunier, P., Jeantet, A. Y., & Rainbow, P. S. (2003). Trace-metal detoxification and tolerance of the estuarine worm *Hediste diversicolor* chronically exposed in their environment. *Marine Biology, 143*(4), 731-744. https://doi.org/10.1007/s00227-003-1124-6

Negus, C. L. (1966). A quantitative study of growth and production of unionid mussels in the River Thames at Reading. *The Journal of Animal Ecology*, 513-532. https://doi.org/10.2307/2489

Newell, C. R., & Hidu, H. (1982). The effects of sediment type on growth rate and shell allometry in the soft shelled clam Mya arenaria L. *Journal of Experimental Marine Biology and Ecology*, *65*(3), 285-295. https://doi.org/10.1016/0022-0981%2882%2990060-0

Orton, J. H. (1928). On Rhythmic Periods in Shell-growth in 0. edulis with a Note on Fattening. *Journal of the Marine Biological Association of the United Kingdom*, *15*(2), 365-427. https://doi.org/10.1017/S0025315400009498

Parry, G. D. (1978). Life history strategies of five species of intertidal limpet. *Ph. D. thesis, University of Melbourne*.

Pathy, D. A., & Mackie, G. L. (1993). Comparative shell morphology of Dreissena polymorpha, Mytilopsis leucophaeata, and the" quagga" mussel (Bivalvia: Dreissenidae) in North America. *Canadian Journal of Zoology*, *71*(5), 1012-1023. https://doi.org/10.1139/z93-135

Phuong, T. T. M. (2014). *Bioaccumulation of heavy metals in Nha Trang bay, Khanh Hoa, Viet Nam* (Doctoral dissertation, Université Nice Sophia Antipolis). https://theses.hal.science/tel-01080132v1/document

Rainbow, P. S. (2002). Trace metal concentrations in aquatic invertebrates: why and so what?. *Environmental pollution, 120*(3), 497-507. https://doi.org/10.1016/S0269-7491(02)00238-5

Rajagopal, S., van der Velde, G. P., Jenner, H. A., & den Hartog, C. (2006). Factors affecting the morphological variation in the mussel *Perna viridis* (Linnaeus, 1758), with emphasis on wave exposure. *Marine Ecology Progress Series, 319*, 107–118. https://doi.org/10.3354/meps319107.

Rajagopal, S., Venugopalan, V. P., Nair, K. V. K., Van der Velde, G., & Jenner, H. A. (1998). Settlement and growth of the green mussel Perna viridis (L.) in coastal waters: influence of water velocity. *Aquatic Ecology, 32*(4), 313-322. https://doi.org/10.1023/A:1009941714978.

Requieron, E. A., Torres, M. A. J., & Demayo, C. G. (2012). Applications of relative warp analysis in describing of scale shape morphology between sexes of the snakehead fish *Channa striata*. *International Journal of Biological, Ecological and Environmental Sciences, 1*(6), 205-209.

Rhoads, D. C., & Pannella, G. (1970). The use of molluscan shell growth patterns in ecology and paleoecology. *Lethaia, 3*(2), 143-161. https://doi.org/10.1111/j.1502-3931.1970.tb01854.x

Rodríguez-Marín, N., Hardisson, A., Gutiérrez, Á. J., Luis-González, G., González-Weller, D., Rubio, C., & Paz, S. (2019). Toxic (Al, Cd, and Pb) and trace metal (B, Ba, Cu, Fe, Mn, Sr, and Zn) levels in tissues of slaughtered steers: Risk assessment for the consumers. *Environmental science and pollution research, 26*(28), 28787-28795. https://doi.org/10.1007/s11356-019-06090-1

Rohlf, F. J., & Marcus, L. F. (1993). A revolution morphometrics. *Trends in Ecology & Evolution*, *8*(4), 129-132. https://doi.org/10.1016/0169-5347(93)90024-J

Rufino, M. M., Albouy, C., & Brind'Amour, A. (2021). Which spatial interpolators I should use? A case study applying to marine species. *Ecological Modelling*, *449*, 109501. https://doi.org/10.1016/j.ecolmodel.2021.109501

Rufino, M. M., Mendo, T., Samarao, J., & Gaspar, M. B. (2023). Estimating fishing effort in small-scale fisheries using high-resolution spatio-temporal tracking data (an implementation framework illustrated with case studies from Portugal). *Ecological Indicators*, *154*, 110628. https://doi.org/10.1016/j.ecolind.2023.110628

Saritha, K., Mary, D., & Patterson, J. (2015). Nutritional status of green mussel *Perna viridis* at Tamil Nadu, Southwest Coast of India. *Journal of Nutrition Food Sciences, 14*(003).https://doi.org/10.4172/2155-9600.S14-003

Seed, R. (1968). Factors influencing shell shape in the mussel Mytilus edulis. *Journal of the Marine Biological Association of the United Kingdom*, *48*(3), 561-584. https://doi.org/10.1017/S0025315400019159

Seed, R. (1980). Shell growth and form in the Bivalvia. *Skeletal growth of aquatic organisms*, 23-61.

Shahabuddin, A. M., Wahab, M. A., Miah, M. I., & Salam, M. A. (2010). Abundance, distribution and culture potentials of three commercially important mollusks species along the coast of Bay of Bengal. *Research Journal of Agriculture and Biological Sciences, 6(*6), 754-762. http://www.aensionline.com/rjabs/rjabs/2010/754-762.pdf

Sivalingam, P. M. (1977). Aquaculture of the green mussel, Mytilus viridis Linnaeus, in Malaysia. *Aquaculture*, *11*(4), 297-312. https://doi.org/10.1016/0044-8486(77)90079-5

Smith, K. L., & Taylor, D. J. (2018). Salinity and shell morphology in marine mussels. *Journal of Marine Ecology, 39*(1), 67–78.

Soon, T. K., & Ransangan, J. (2014). A review of feeding behavior, growth, reproduction and aquaculture site selection for green-lipped mussel, Perna viridis. *Advances in Bioscience and Biotechnology*, *5*(5), 462-469. http://dx.doi.org/10.4236/abb.2014.55056

Sreenivasan, P. V. (1983). Reproductive cycle of the green mussel *Perna viridis* (Linnaeus) from Porto Novo waters, east coast of India. *Aquaculture, 30*(1–4), 39–53.

Sreenivasan, P. V., Kumar, N., & Rajan, R. (2020). Economic significance of mussel aquaculture in South Asia: A review. *Marine Aquaculture Journal, 29*(2), 78–89.

Stanley, S.M. (1970). Relation of Shell Form to Life Habits of the Bivalvia (Mollusca). *Geological Society of America Memoirs, 125,* 1-282. https://doi:10.1130/MEM125-p1

Sutherland, J. P. (1970). Dynamics of high and low populations of the limpet, Acmaea scabra (Gould). *Ecological Monographs*, *40*(2), 169-188. https://doi.org/10.2307/1942294

Tan, K. S., & Ransangan, J. (2017). Feeding behaviour of green mussels, *Perna viridis* farmed in Marudu Bay, Malaysia. *Aquaculture Research, 48*(3), 1216-1231. https://doi.org/10.1111/are.12963

Thayer, C. W. (1975). Morphologic adaptations of benthic invertebrates to soft substrata. *ournal of Marine Research* 33, (2). https://elischolar.library.yale.edu/journal_of_marine_research/1316

Uba, K. I. N. (2021). Determining shell shape differences in the horse mussels Modiolus philippinarum (Hanley 1843) and Modiolus modulaides (Röding 1798) by morphometric analysis. *Philippine Journal of Science*, *150*(4), 743-752. https://doi.org/10.56899/150.04.12

Urdy, S., Goudemand, N., Bucher, H., & Chirat, R. (2010). Allometries and the morphogenesis of the molluscan shell: a quantitative and theoretical model. *Journal of Experimental Zoology Part B: Molecular and Developmental Evolution*, *314*(4), 280-302. https://doi.org/10.1002/jez.b.21337?urlappend=%3Futm_source%3Dresearchgate

Villaluz, C. G. B., Tolete, J. C., Almocera, F. B., Janti, M. J., Pilar, T. J. E., Torres, M. A. J., & Requieron, E. A. (2016). Morphological variations of green mussel (*Perna viridis*) in Bula, General Santos city using geometric morphometric analysis. *Journal of Biodiversity and Environmental Sciences (JBES), 8,* 216-224. https://innspub.net/wp-content/uploads/2022/10/JBES-V8-No2-p216-224.pdf.

Wang, W., Ho, Y. L., and Liu, C. M. (2020). Effects of Microplastic Exposure on Shell Shape and Growth in Perna viridis: A Geometric Morphometric Study. *Ecotoxicology and Environmental Safety 196*: 110523. https://doi.org/10.1016/j.ecoenv.2020.110523.

Yap, C. K., Ahmad Wakid, S., Chew, J. M., Sutra, J., Syazwan, W. M., Aziz, N. A. A., ... & Cheng, W. H. (2023). Shell Deformities in the Green-Lipped Mussel Perna viridis: Occurrence and Potential Environmental Stresses on the West Coast of Peninsular Malaysia. *Pollutants*, *3*(3), 406-418. https://doi.org/10.3390/pollutants3030028

Yap, C. K., Edward, F. B., & Tan, S. G. (2010). Heavy metal concentrations (Cu, Pb, Ni, and Zn) in the surface sediments from a semi-enclosed intertidal water, the Johore Straits: Monitoring data for future reference. *Journal of Sustainability Science and Management, 5*(2), 44–57.

Yap, C. K., Edward, F. B., Syazwan, W. M., Azrizal-Wahid, N., Cheng, W. H., Tan, W. S., ... & Bintal, A. (2022). Soluble potentially toxic metals (Cu and Pb) in the different tissues of marine mussel perna viridis: health risk perspectives. In *Marine Biochemistry* (pp. 69-80). CRC Press. https://shorturl.at/XTsFR

Yonge, C. M., & Campbell, J. I. (1968). II.—On the heteromyarian condition in the bivalvia with special reference to Dreissena polymorpha and certain Mytilacea. *Earth and Environmental Science Transactions of The Royal Society of Edinburgh*, *68*(2), 21-42. https://doi.org/10.1017/S0080456800014502

Zelditch, M., Swiderski, D., & Sheets, H. D. (2012). *Geometric morphometrics for biologists: A primer*. Academic press.