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Research Article

Phenotypic plasticity of shell shape and growth of mussels to environmental conditions: *Mytella strigata* in the southeast Gulf of California

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ABSTRACT. The shape of the shell and the development of bivalve mollusks are strongly associated with the action of environmental conditions. The environmental variables, functional parameters of the shell, and the relative growth of *Mytella strigata* were seasonally (summer 2020 to spring 2021) determined in three locations: Altata Bay (AB), Macapule Lagoon (ML) and El Colorado Bay (CB) from the southeast Gulf of California (Mexico). Shell dimensions (SL: shell length, SH: shell height, and SW: shell width) showed significant differences. ML mussels obtained the highest measurements (SL = 19.12 ± 1.60 mm, SH = 47.67 ± 3.92 mm, SW = 14.92 ± 1.04 mm, and body weight = 7.54 ± 1.40 g). The greatest shell elongation (SH/SL) was observed in ML (2.49 ± 0.13), while CB recorded the highest compactness and convexity values. SH/SL was the most substantial interaction (R^2 = 0.67, 0.63, and 0.55 in AB, ML and CB, respectively). The principal component analysis shows three groupings of the biometric indicators and the relative growth of mussels concerning the environmental parameters in each lagoon. The environmental conditions affected the shape of the shell and relative growth of *M. strigata* in the three lagoons, emphasizing the type of habitat and salinity as the determining factors. The shell phenotypic plasticity of this mussel represents an adaptive strategy of resilience to the environmental factors in each place.

Keywords: *Mytella strigata*; bivalves; shell biometrics; allometry; environmental parameters; mussel; Gulf of California

INTRODUCTION

The shell of mollusks is an external protective structure mainly composed of calcite and aragonite, crystalline forms of $CaCO_3$, and a small amount of organic matter (Grefsrud et al. 2008). Depending on the species, they present different arrangements, from prisms and nacre to crossed or needled lamellae (Clark et al. 2020). The construction of such formations is dictated, in the first instance, by the genetic information of each species; however, the phenotypic variability of the shell is strongly influenced by biotic and abiotic factors, such as environmental parameters, parasitism, food, waves, substrate, predation, and desiccation, among others (Mininguez et al. 2012, Babarro et al. 2016, Telesca et al. 2019). Also, the industrial waste derived from human activities is discharged into the water bodies where many of these organisms inhabit, exerts their shell's biomineralization, development, and shape (Lopes-Lima et al. 2012, Stewart et al. 2021).

Béguinot (2018) mentions that the physical state of mollusks can be evaluated by considering the shape and

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development of their shells. Using functional parameters of the shell (elongation, compaction, and convexity) that relate the linear dimensions (height, length, and width of the shell; Modestin 2017) represents a valuable tool to evaluate changes in its shape. On the other hand, the parameters associated with growth (allometry or relative growth) allow for determining the relationship between the dimensions mentioned above (Sotelo-Gonzalez et al. 2020). Thus, the intraspecific variations in the shape of the shell and the growth of a species living in different locations can be characterized based on the effect of environmental and anthropogenic factors in each area (Scalici et al. 2017). Therefore, the mollusk shell represents a biological archive that confers knowledge of the resilience of a population in different zones over time. The mussel *Mytella strigata* (Hanley, 1843) is an endemic species from the coasts of the Pacific Ocean, found from Baja California to Peru (Lodeiros et al. 2021). Currently, it is distributed in many parts of the world, where it is considered an invasive species due to its easy adaptation and reproduction (Calazans et al. 2017, Sanpanich & Wells 2019). This mussel lives attached to the roots of mangroves or buried in the substrate in the coastal lagoons or estuaries in the southeast Gulf of California; local fishing communities do not consume it, but because it is sessile and a filter feeder, it is mainly used as a biological monitor in environmental studies (Ruelas-Inzunza & Páez-Osuna 2000, Ruiz-Fernández et al. 2018). Since the Gulf of California is subject to constant effects of climate change (Páez-Osuna et al. 2016) and strong anthropogenic pressure (Páez-Osuna et al. 2017, Sepúlveda et al. 2020), it is essential the evaluation that exerts these factors in organisms -as mussels- that store biological signals in their phenotypic expression such as the shape of the shell and its allometry.

Therefore, this study aims to determine the shell's functional parameters and the relative growth of *M. strigata* in three wild populations from the southeast Gulf of California. Our hypothesis establishes that the functional and growth parameters of the shell of this *M. strigata* will present differences related to the environmental (natural and anthropogenic) conditions of each place.

MATERIALS AND METHODS

Study location

Specimens were collected in three lagoons in the state of Sinaloa (southeast Gulf of California, Mexico): Altata Bay (AB), located in the Altata-Ensenada del Pabellón complex, in the municipality of Navolato (24°20'-24°35'N and 107°20'-107°55'W; Góngora-Gómez et al. 2018); Macapule Lagoon (ML), located within the San Ignacio-Navachiste-Macapule Lagoon system, in the municipality of Guasave (25°18'-25°24'N and 108°32'-108°45'W; Sepúlveda et al. 2022); and El Colorado Bay (CB), belonging to the municipality of Ahome (25°43'-25°60'N and 109°23'-109°51'W; Góngora-Gómez et al. 2022). The three lagoons (Fig. 1) are characterized by being connected to the Sea of Cortez through one or several mouths that permanently maintain a marine environment within them. The climate in the three regions is warm to semi-dry (24°C average annual temperature), with rains during summer, which causes rainfall between 300 and 600 mm per year (Muñoz-Sevilla et al. 2017). In addition, there are forests of various mangrove species (red mangrove, *Rhizophorae mangle* (Linnaeus, 1753); buttonwood mangrove, *Conocarpus erectus* (Linnaeus, 1753); white mangrove, *Laguncularia racemose* (Linnaeus, 1753); and black mangrove, *Avicennia germinans* (Linnaeus, 1764) that are indistinctly distributed around them (Sepúlveda et al. 2022). Also, various kinds of intense anthropogenic activities are carried out in each lagoon.

Four samplings were carried out (summer, autumn 2020, winter, and spring 2021) in each lagoon, extracting 150 organisms per annual season (n = 600). In the spring 2021 sampling in Guasave (ML), all the mussels sampled *in situ* were found dead, so the number of observations for this locality was n = 450. The AB and CB specimens were detached in clusters from mangrove roots with the help of a knife, while ML mussels were collected from the muddy substrate at the outlet of an urban drainage canal. All samplings were carried out during low tide. The shells were cleaned with plastic brushes to remove organic matter and detach the epibiont fauna; finally, they were placed in plastic containers and transferred to the Malacology Laboratory of the National Polytechnic Institute-Interdisciplinary Research Center for Regional Integral Development - Sinaloa Unit (IPN-CIIDIR-Sinaloa, by its Spanish acronym).

The physical and chemical parameters of the water were registered in each sampling. Temperature and dissolved oxygen (DO) were obtained with an oxygen meter (YSI, 55/12 FT, Ohio 45387). For salinity, a precision refractometer (Atagon S/Mill) was used. The pH was determined with a potentiometer (Hanna HI 8314); transparency and depth were measured with a Secchi disk (Góngora-Gómez et al. 2020). Also, water samples were obtained to determine chlorophyll-*a*

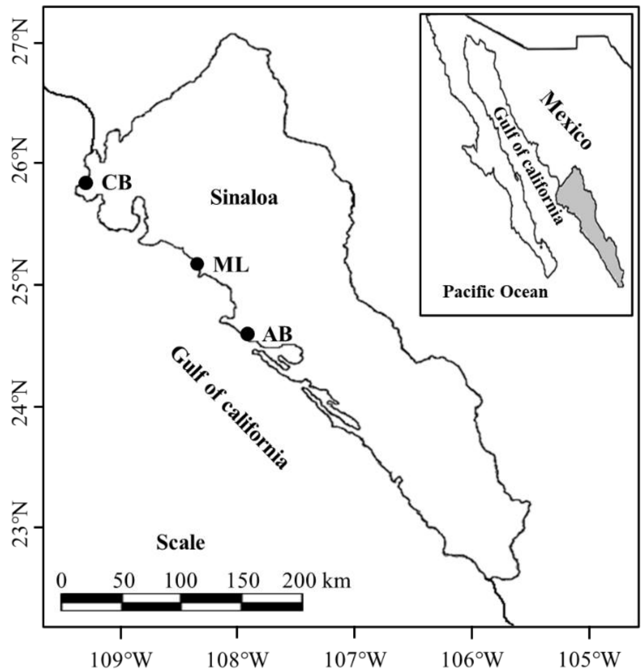

Figure 1. Location of the sampling sites of the mussel *M. strigata* in the lagoons from the north-central coast of Sinaloa (Mexico): El Colorado Bay (CB), Macapule Lagoon (ML), and Altata Bay (AB).

(Chl-*a*), total suspended solids (TSS), organic solids (OS), and inorganic solids (IS). The samples were placed in a cooler and transported to the laboratory for further analysis. TSS, OS, and IS concentrations were determined according to the standard methodology (APHA 1995). The concentration of Chl-*a* was obtained using the spectrophotometric technique proposed by Strickland & Parsons (1972).

Biometrics and morphometry

The mussels collected in each lagoon were measured to obtain the biometric indexes of their shell (height, length, and width) with a digital Vernier (0.01 mm, Mitutoyo, CD-8" CS) and body weight (BW) using a portable balance (0.01 g, OHAUS, Scout Pro SP 2001). Descriptive statistics (mean, standard deviation, coefficient of variation, and minimum and maximum values) were used to report total shell dimensions and BW data. An analysis of variance and a Tukey test was performed to detect and highlight statistical differences between the mussel dimensions and the biometric indices (α = 0.05). Individual shell length (SL: maximum distance between the anterior and posterior margins), shell height (SH: the maximum distance from the umbo to the ventral margin), and shell width (SW: maximum distance between the thickest parts of the valves) were used to obtain the biometric indicators: elongation (SH/SL), roundness or compactness (SW/SL) and convexity (SW/SH) (Selin, 2007, Modestin, 2017).

All data set was subjected to the Durbin-Watson test to eliminate outliers, and the normality of the residuals was analyzed using the quantile-quantile Pplot plot (Q-Q Plot) (RStudio Program, R Core Team 2018). The morphometric relationships between the different shell dimensions (SL/SH, SL/SW, and SH/SW) for *M. strigata* from each lagoon were estimated using the linear equation Y = *b*X + *a*, where Y and X: dimensions of the shell (SL, SH, and SW, mm); *a*: intercept, and *b*: slope. The coefficient b = 1 indicates a relative isometric growth, applicable when variables with the same unit of measure are associated. The Spearman correlation coefficient (*r*) was used to analyze the data's goodness of fit (Sokal & Rohlf 1995).

Statistics

A multiple correlation analysis (Spearman) was performed with the average values of all the parameters and indicators of the annual seasons for each sampling site; also, a principal component analysis (PCA) was used to determine the environmental factors that could influence the biometric indexes and the relative growth of *M. strigata* in the three lagoons.

RESULTS

Water physical and chemical parameters are shown (Fig. 2). The average water temperature showed a similar pattern in the three sampling locations, with a decrease in winter. The highest gradient (34°C in AB) was obtained in the summer of 2020, while the lowest (21.3°C in ML) was recorded in winter 2021. Annual seasonal salinity concentration varied among sites, ranging from 35 to 45 in CB to 22 to 42 in AB. The three lagoons' pH and DO showed different patterns for the four annual seasons. In the fall of 2020, the pH in ML (8.21) was higher than in AB (7.69). In the summer of 2020, the DO in ML registered the lowest value (1.8 mg L^{-1}), while concentrations greater than 5.5 mg L^{-1} were obtained in AB and CB. The concentration of Chl-*a* presented an interval from 47.97 mg m^{-3} in AB to 1.64 mg m^{-3} in CB, both in autumn 2020, while a higher level of solids (TSS, OS, and IS) was observed in AB during the four annual seasons.

Water depth in AB, ML, and CB ranged from 0.5 m in winter to 1.3 m in autumn, 0.4 m in summer to 0.8 m in winter, and 0.0 m in autumn to 0.71 m in winter, respectively; meanwhile, transparency of water in AB, ML, and CB, respectively ranged from 0.3 m in summer to 0.84 m in spring, from 0.0 m in fall to 0.8 m in winter, and from 0.0 m in fall to 0.37 m in spring.

Shell dimensions of *M. strigata* in the three study sites showed significant differences ($P < 0.05$) (Table 1). ML mussels obtained the highest measurements (SL = 19.12 ± 1.60 mm, SH = 47.67 ± 3.92 mm, SW = 14.92 ± 1.04 mm and BW = 7.54 ± 1.40 g). The coefficient of variation (CV) ranged from 6.98% for the SW of the ML mussels to 18.67% for the SW of the AB bivalves. AB recorded the highest CV for total body weight in the mussels.

The shell biometric indexes for the three populations of *M. strigata* were different ($P < 0.05$). The greatest shell elongation was observed in ML, while the highest values of compaction and convexity were recorded for the CB population (Table 2).

The morphometric relationships of the shell dimensions (SH/SL, SW/SL, and SW/SH) were linear and positive for the three mussel populations (Fig. 3); furthermore, the value of the slope ($b > 1$) for the SH/SL interaction indicated a relative growth of positive allometric type, while the SW/SL and SW/SH relationships presented negative allometry ($b < 1$). The highest values of the coefficient of determination (R^2) for each morphometric relationship were obtained in the specimens of the AB population. SH/SL was the most substantial interaction (SH/SL) in the three mussel populations (R^2 = 0.67, 0.63, and 0.55 in AB, ML and CB, respectively). The highest R^2 (0.76) was obtained for SW/SH in BA.

Most of the studied correlations showed a relationship ($P < 0.05$) between the water's physical, chemical, and biological parameters in the three sites (Table 3) and presented an interval of r_s = -0.99 to 1. The dimensions of the shell were positively associated with total mussel weight in AB (SH/BW, $r_s = 0.97$, $P = 0.02$; SW/BW, $r_s = 0.96$, $P = 0.03$), and CB (SH/BW, $r_s = 0.98$, $P = 0.01$; SL/BW, $r_s = 0.95$, $P = 0.04$; SW/BW, $r_s = 0.99$, $P = 0.05$). Correlations between relative growth and biometric indexes of *M. strigata* with water parameters were obtained in AB and ML. Shell compaction and convexity were associated in mussels from AB and ML ($r_s = 0.99$, $P = 0.02$; and $r_s = 1$, $P = 0.05$, respectively).

Of the variances of all the variables analyzed (20) in the three sites, the eigenvalues of three components in AB and CB and two components in ML satisfactorily explain their correlations. The points obtained in the PCA for *M. strigata* in the three lagoons show three groupings of the biometric indicators and the relative growth concerning the environmental parameters in each lagoon (Fig. 4), with dispersion values from -0.42 to 0.45 in AB, from -0.33 to 0.33 in ML, and from -0.38 to 0.33 in CB. In AB, salinity directly influenced the biometric indicators (elongation, compaction, and convexity), while in ML, water temperature and salinity directly affected the relative growth of *M. strigata* (*b* SL/SW, *b* SW/SW, and *b* SL/SH). In the CB lagoon, the salinity is correlated with compaction and elongation of the mussel shell, while TSS and IS correlated with convexity and relative growth (*b* SL/SH and *b* SL/SW).

DISCUSSION

One of the most critical environmental factors that affect the shape and biometric proportions of the shell in bivalve mollusks is latitude (Beukema & Meehan 1985) and all the load of local parameters (natural or anthropogenic) inherent in each region (Gizzi et al. 2016). Although the three bodies of water are in a region categorized with climate subtropical or temperate with dry summer (Chen & Chen 2013), less than 120 km apart, most of the environmental parameters -except for the water temperature- showed variations in the year's seasons. For example, the salinity in AB (22-43) or the pH in ML (7.83-8.2) during the summer and autumn of 2020 presented different patterns than the other lagoons. The same

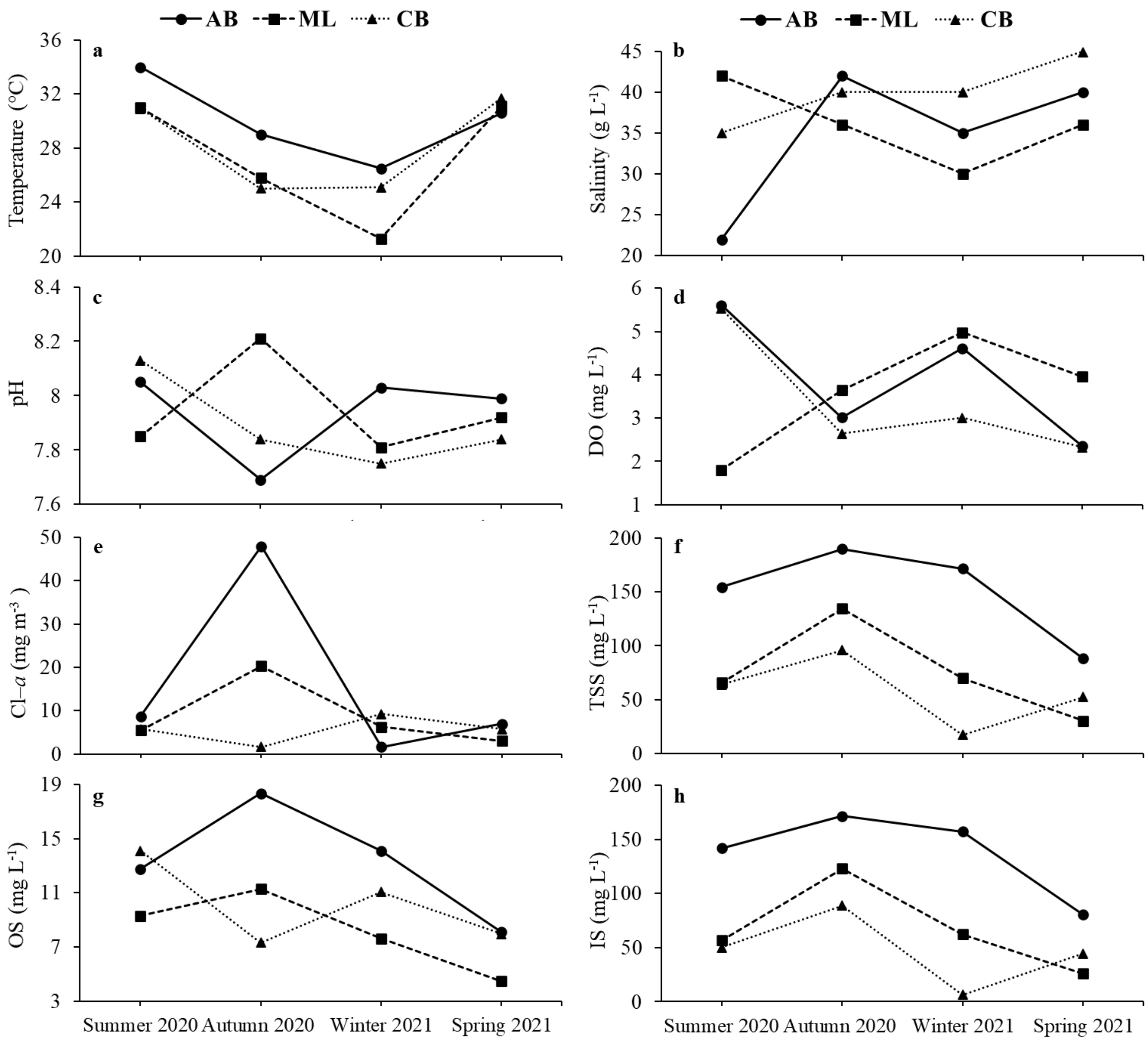

Figure 2. Water physicochemical parameters at the three sampling sites of the southeast Gulf of California (Mexico): AB: Altata Bay, ML: Macapule Lagoon, and CB: El Colorado Bay. a) temperature (°C); b) salinity (g L^{-1}); c) pH; d) dissolved oxygen (DO, mg L^{-1}); e) chlorophyll-*a* (Chl-*a*, mg m^{-3}); f) total suspended solids (TSS, mg L^{-1}); g) organic solids (OS, mg L^{-1}); h) inorganic solids (IS mg L^{-1}).

happened for the DO concentration in ML during the summer of 2020, when a concentration of 1.8 mg L^{-1} was recorded, while the level of this gas in the water exceeded 5 mg L^{-1} in AB and CB. This same trend was observed for food supplies, especially for Chl-*a*, whose concentration in AB was 96.6% higher than that obtained in CB in the same annual season (autumn 2020).

In various studies carried out in the same lagoons by our research group, it is possible to observe similar fluctuations in the range of environmental parameters. For example, Góngora-Gómez et al. (2020) reported wide temperature ranges (18.8-33.3°C), salinity (24.5-38.5), DO (3.8-7.8 mg L^{-1}), pH (4.8-8.6), TSS (22.7-83.2 mg L^{-1}), and Chl-*a* (1.1-14.2 mg m^{-3}) in several commercial production cycles of the mangrove oyster *Crassostrea corteziensis* (Hertlein, 1951) carried out in ML. The same trend was observed in CB for the black clam *Chionista fluctifraga* (G.B. Sowerby II, 1853) (Góngora-Gómez et al. 2022), in which the intervals were: temperature = 15.9-32.1°C, salinity = 25-40, DO = 5.7-9.6 mg L^{-1}, pH = 4.3-8.2, TSS = 19.3-189.2 mg L^{-1}, and Chl-*a* = 2.2-10.5 mg m^{-3}. On the other hand, Góngora-Gómez et al. (2019) obtained a more stable temperature (22.5-30.8°C), salinity (30.3-35.6), DO (3.1-8.1 mg L^{-1}), and pH (7.5-8.1) margins in AB for 13 months working with the Japanese oyster, *Magallana* (*Crassostrea*) *gigas* (Thunberg, 1793). However, the

Table 1. Shell biometric parameters of *M. strigata* from the three southeast Gulf of California sites. SD: standard deviation, Max: maximum value, Min: minimum value, CV: coefficient of variation, SL: shell length, SH: shell height, SW: shell width, BW: body weight. A column with different superscript letters denotes significant differences ($P < 0.05$) among the sampling sites.

Site	SL (mm)	SH (mm)	SW (mm)	BW (g)
Altata Bay				
Mean	18.44[b]	41.97[b]	13.63[a]	5.97[b]
SD	2.12	6.18	2.55	2.28
Max	25.17	85.33	46.32	14.4
Min	11.63	17.5	1.5	2.1
CV	11.49	14.72	18.67	38.11
Macapule Lagoon				
Mean	19.12[c]	47.67[c]	14.92[c]	7.54[c]
SD	1.60	3.92	1.04	1.40
Max	23.85	59.23	18.62	12.5
Min	14.75	32.67	11.94	4.1
CV	8.35	8.23	6.98	18.55
El Colorado Bay				
Mean	17.89[a]	39.84[a]	14.25[b]	5.82[a]
SD	1.66	3.07	1.29	1.24
Max	22.53	49.42	19.93	9.3
Min	13.72	31.3	10.34	2
CV	9.30	7.69	9.02	21.23
F-value	134.02	453.24	65.88	151.26
P-value	0.0001	0.0001	0.0001	0.0001

behavior of all the parameters studied showed an annual seasonal variation in the three lagoons that influenced the shell's functional variables and allometry of *M. strigata*.

In addition to the environmental variables, the effect of anthropogenic pressure could have contributed to the differences in the shape of the shell and the relative growth of the mussel, as reported by Yee-Duarte et al. (2017) for a population of the chocolata clam *Megapitaria squalida* (G.B. Sowerby I, 1835) closed to a mining area in the west of Gulf of California. For example, the AB lagoon has an area of 8800 ha; it receives untreated water discharges from the municipalities of Navolato (154,352 inhabitants) and Culiacán (905,265 inhabitants), and the waste from intensive agriculture that is practiced in the surroundings, which corresponds to approximately 116,409 ha of cultivation. In addition, waste from 17,511 ha destined for shrimp farming and chicken fattening (57,624,911 chickens yr^{-1}) is dumped into this lagoon, and it is also subjected to tourist and fishing activities (Frías-Espericueta et al. 2008, Sepúlveda et al. 2020). Although the ML (3,800 ha) is a protected natural area categorized as a RAMSAR site within the Gulf of California, it is an area strongly impacted by the discharge of waste generated in 18,735 ha dedicated to shrimp farming, the chemical products used in 119,994 agricultural hectares that are discharged into canals that flow into the lagoon, and the urban and industrial waste produced by the city of Guasave (295,353 inhabitants). Also, fishing and producing approximately 77,785 chickens annually represent relevant activities in this area (Jonathan et al. 2017). In the case of CB (11,500 ha), a large area of extensive agriculture (189,064 ha), municipal urban waste (449,215 inhabitants), chemical compounds used in 12,639 ha for shrimp farming, the production of approximately 94,422 pigs per year, and activities such as traditional fishing (Páez-Osuna & Osuna-Martínez 2015, CESASIN 2020, INEGI 2020, SIAP 2020, Sepúlveda et al. 2022), contribute to its pollution and eutrophication, exerting a substantial impact on this body of water.

It is important to note that *M. strigata* not only lives attached to various surfaces (mangrove roots, boats, rocks; Estévez & Estuardo 1977, Jayachandran et al. 2019), as was the case of the AB and CB populations, but it is also possible to find it buried in the sediment (Carneiro-Beltrão et al. 2022), as happened for the ML population. In both cases, the mussel uses the byssus to attach to the bark of the mangrove or other organisms or each other, respectively. There were two trends in the results, apparently dictated by the mussel habitat (attached to mangrove for AB and CB *vs*. buried in sediment for ML). While, in the mangrove, the organisms are exposed to currents, waves, and weather conditions, causing their growth to be slower and the shape of their shell more cupped, the organisms within the substrate reduce their energy expenditure and hydrodynamic friction (Akester & Martel 2000). The aforementioned is characteristic of bivalves whose shell shape is rather elongated (Telesca et al. 2018), as observed in ML mussels. Specifically, the greater average size and weight of *M. strigata* in ML could be attributed to the protection conferred by the place where it lives (buried approximately 5-10 cm in the sandy-muddy bottom), free from predators and the effect of external stress factors such as waves and currents. In agreement, Kandratavicius & Brazeiro (2014) found that the blue mussel, *Mytilus edulis platensis* (Linnaeus, 1758), has larger sizes and BW when kept in protected places. On the other hand, Seed (1968) mentions that the absence of predators in populations of the mussel *M. edulis* is associated with the presence of specimens with a more elongated shell, with the ability to dig and anchor in the sediment (Levine et al. 2014), as happened in ML. However,

Table 2. Biometric indices of mussels collected in three coastal lagoons in the southeast Gulf of California. SL: shell length, SH: shell height, SW shell width, AB: Altata Bay, ML: Macapule Lagoon, CB: El Colorado Bay. Rows with different superscript letters denote significant differences ($P < 0.05$) among the sampling sites.

Biometric index	AB	ML	CB	*F*-value	*P*-value
Elongation (SH/SL)	2.27 ± 0.23^b	2.49 ± 0.13^c	2.23 ± 0.15^a	284.82	0.0001
Compactness (SW/SL)	0.74 ± 0.11^a	0.78 ± 0.05^b	0.80 ± 0.08^c	79.20	0.0001
Convexity (SW/SH)	0.32 ± 0.05^b	0.31 ± 0.02^a	0.36 ± 0.03^c	187.70	0.0001

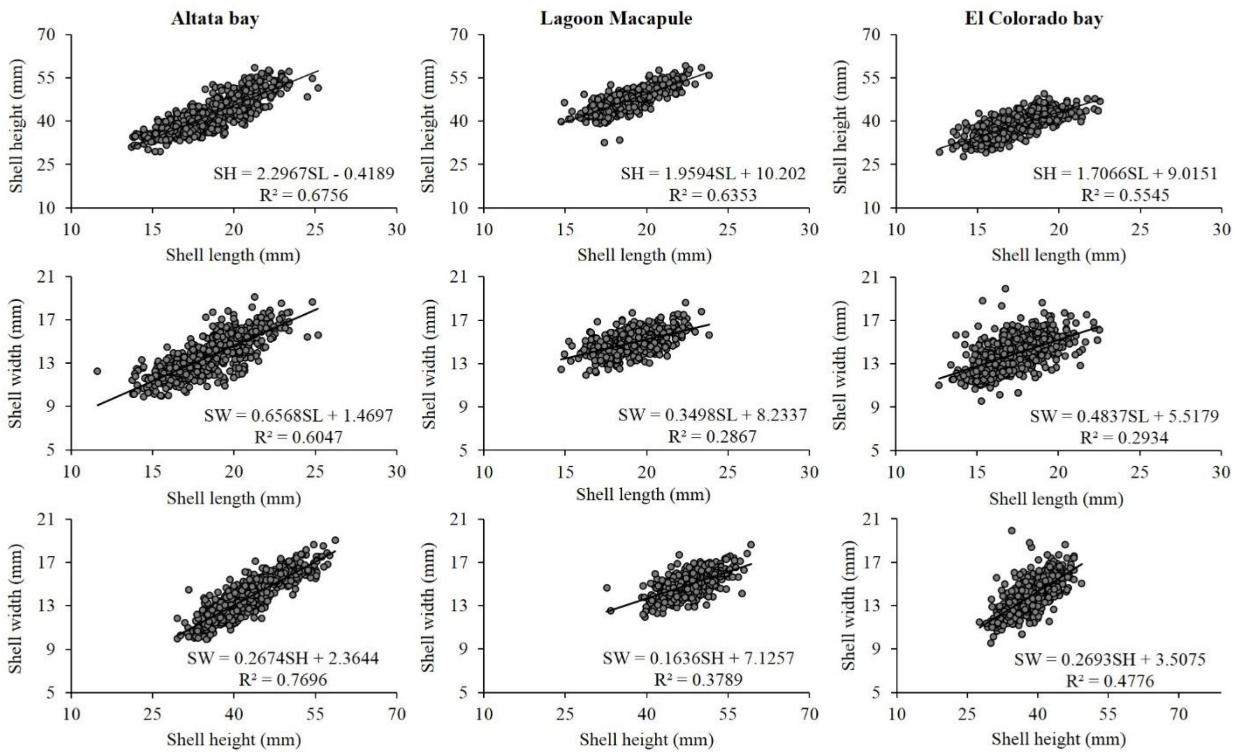

Figure 3. Morphometric relationships of shell biometrics in *M. strigata* from the three southeast Gulf of California sites. R^2: coefficient of determination. SW: shell width, SH: shell height.

being buried, the ML mussels were also exposed to the constant contribution and accumulation of different wastes from the urban drainage channel towards the sediment, which could have caused the mortality of the entire population in the spring 2021 sampling.

In addition to being the largest and heaviest specimens, the shape of the shell of the mussels in ML was more elongated and flatter, with the highest SL but less convexity. In contrast, the specimens from AB and CB were slightly more cupped or oblong but smaller. Seed (1968) also mentions that mussels with a more compressed shell are longer, which would be influenced by various factors such as environmental variables, density, substrate, and age, among others.

The adaptive strategy of this species to the different environmental and anthropogenic conditions in each lagoon contributes, to a certain extent, to the expression of its phenotype exhibited by the shape of its shell (Telesca et al. 2018). Due to endogenous (age, size, reproductive maturity) and exogenous factors (environment, density, sediment), the development of the dimensions of the shell in bivalves may show modifications that do not represent proportionality or isometry; what happened in the three populations studied, whose relative growth was allometric (positive for SL/SH, $b > 1$; and negative for SL/SW and SH/SW, $b < 1$). The morphometric indices revealed morphological differences of mussels between different lagoons, partially being size-dependent, suggesting changes in shell shape according to its development (Vasconcelos et al. 2021). The regression equations in the three lagoons show a consistent pattern in the type

Table 3. Spearman correlations (r_s) among environmental parameters, relative growth, and biometric indexes of the mussel *M. strigata* from three coastal lagoons in the southeast Gulf of California. TRANS: transparency, DO: dissolved oxygen, SAL: salinity, T°C: temperature, IS: inorganic solids, OS: organic solids, TSS: total suspended solids, Chl-*a*: chlorophyll-*a*, SL: shell length, *b*: slope of relative growth, SH: shell height, SW: shell width, BW: body weight, COMP: shell compactness, CONV: shell convexity, ELONG: shell elongation. Only significant correlations (P < 0.05) are included.

Variables	AB	Variables	ML	Variables	CB
TRANS *vs*. pH	-0.99 (P = 0.00)	IS *vs*. Cl-*a*	0.99 (P = 0.01)	T°C *vs*. TRANS	0.97 (P = 0.01)
DO *vs*. TRANS	-0.99 (P = 0.00)	TSS *vs*. Cl-*a*	0.99 (P = 0.00)	IS *vs*. TSS	0.99 (P = 0.00)
IS *vs*. TSS	0.99 (P = 0.00)	T°C *vs*. DO	-0.99 (P = 0.03)	TSS *vs*. Cl-*a*	-0.98 (P = 0.01)
OS *vs*. TSS	0.95 (P = 0.04)	SAL *vs*. T°C	0.99 (P = 0.02)	IS *vs*. Cl-*a*	-0.99 (P = 0.00)
Chl-*a* *vs*. Ph	-0.97 (P = 0.02)	IS *vs*. TSS	0.99 (P = 0.01)	SH *vs*. BW	0.98 (P = 0.01)
SL *vs*. T°C	0.95 (P = 0.04)	OS *vs*. TRANS	-0.99 (P = 0.03)	SL *vs*. BW	0.95 (P = 0.04)
b SH/SW *vs*. pH	0.95 (P = 0.04)	SAL *vs*. *b* SH/SW	0.99 (P = 0.00)	SW *vs*. BW	0.99 (P = 0.00)
b SL/SH *vs*. Depth	-0.96 (P = 0.03)	OS *vs*. ELONG	-0.99 (P = 0.03)	SH *vs*. SW	0.98 (P = 0.01)
SH *vs*. BW	0.97 (P = 0.02)	T°C *vs*. *b* SH/SW	0.99 (P = 0.02)	SL *vs*. *b* SH/SW	-0.98 (P = 0.01)
SW *vs*. BW	0.96 (P = 0.03)	TRANS *vs*. ELONG	0.99 (P = 0.00)		
COMP *vs*. CONV	0.99 (P = 0.00)	COMP *vs*. CONV	0.99 (P = 0.00)		

of positive allometry for SL/SH and negative for SL/SW and SH/SW, which means that the dimensions of the shell of *M. strigata* are not developed proportionally. It would be explained by its physiology and each locality's environmental and anthropogenic conditions (Gaspar et al. 2001). In addition, the highest coefficient of determination (R^2) for the three morphological associations of the mussel in AB (SL/SH = 0.67, SL/SW = 0.60, SH/SW = 0.76), indicated a moderate allometry in its proportions, being the interaction SH/SW, which best describes its growth.

On the contrary, the development of the ML and CB populations is better explained by the SL/SH relationship, coinciding with what was reported by Somaya et al. (2018) for a population of the date mussel *Lithophaga lithophaga* (Linnaeus, 1758) (R^2 = 0.92, SL/SH) in the eastern Mediterranean Sea. From the above, it is possible to deduce that while the proportion of the dimensions of the shell is greater, its shape will be more uniform (Morán et al. 2022). As mentioned above, any change is attributable to endogenous (species, sexual maturity, age, metabolism) (Rosenberg & Hughes 2007) or exogenous factors (environmental variables and anthropogenic influence) (Gaspar et al. 2002, Sampaio et al. 2022).

The plots of principal component axis 1 and axis 2 in the three lagoons showed three major different groupings of biological and environmental parameters, in which salinity appears as the main factor that would contribute most to the biometric indicators (elongation, compaction, and convexity) in *M. strigata* from AB and CB, and to the three associations that define allometric growth (*b* SL/SH, *b* SL/SW, and *b* SH/SW) of ML mussels. It is well documented that the salinity in shallow coastal water bodies can be drastically modified due to fluctuations by precipitation, evaporation, and continental contribution loaded with anthropogenic materials, becoming an environmental disruptor that modifies the metabolism, immune response, and bivalve physiology (Akberali & Trueman 1985, Haider et al. 2018). Coincident with the present work, salinity would have a determining effect both on the shape of the shell and on the allometry of *M. strigata* in the populations studied, as also indicated by

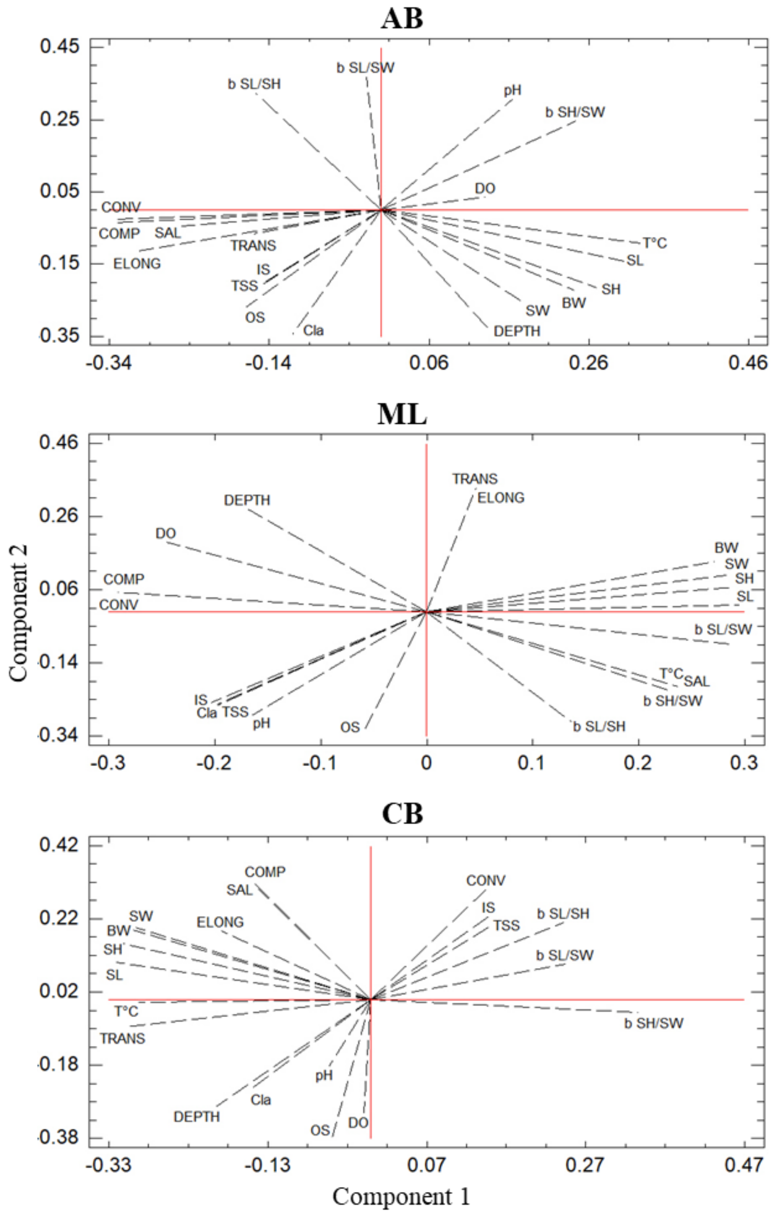

Figure 4. Principal component plots of component 1 and component 2 of biometrics and allometry variables of *M. strigata* from the three sites (AB: Altata Bay, ML: Macapule Lagoon, CB: El Colorado Bay) in the southeast Gulf of California. b SH/SW: the value of the shell height/shell width relationship; b SL/SH: value of the shell length/shell height relationship; b SL/SW: value of the shell length/shell width relationship, BW: body weight, Chl-*a*: chlorophyll-a, COMP: shell compactness, CONV: shell convexity, DEPTH: water depth, DO: dissolved oxygen, ELONG: shell elongation, IS: inorganic solids, OS: organic solids, pH: pH units, SAL: salinity, SH: shell height, SL: shell length; SW: shell width, T°C: temperature, TRANS: transparency, TSS: total suspended solids.

the correlation found between this parameter with *b* SH/SW (r_s = 0.99, P = 0.00) in ML.

CONCLUSION

Derived from the results, it is possible to conclude that, despite the proximity between the study sites, the environmental conditions exerted a different effect on the shape of the shell and relative growth of *M. strigata* in the three lagoons, emphasizing the type of habitat and salinity as the determining factors. At the same time, this species demonstrates phenotypic plasticity to modify the shape of its shell and growth as an adaptive strategy of resilience to the environmental factors evaluated, in addition to the anthropogenic pressure in each place, for which close surveillance is recommended.

Credit author contribution

A.M. Góngora-Gómez: conceptualization, funding acquisition, project administration, methodology, and review; J.A. Hernández-Sepúlveda, methodology, review, and supervision; T.E. Isola, validation, review, and writing; C.H. Sepúlveda, writing, data curation, formal analysis, review, and editing; C.O. Montoya-Ponce, data curation, supervision, review; M. García-Ulloa, conceptualization, validation, methodology, supervision, data curation, formal analysis, funding acquisition, writing, review and editing. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare no potential conflict of interest in this manuscript.

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