Hidrobiológica 2025, 35 (2): 97-107

UNIVERSIDAD AUTÓNOMA METROPOLITANA Unidad Iztapalapa
Casa abierta al tiempo

HIDROBIOLÓGICA
http:/hidrobiologica.izt.uam.mx
ISSN: 2448-7333

OPEN ACCESS
Research Article
August, 2025

Morpho-biometric relationships and allometry of the "black clam" (*Anadara mazatlanica*) from two coastal lagoons in the southeastern Gulf of California

Relaciones morfo-biométricas y alometría de la almeja negra (*Anadara mazatlanica*) de dos lagunas costeras del sureste del Golfo de California

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Recibido: 10 de octubre de 2024. *Aceptado:* 21 de noviembre de 2024. *Publicado:* agosto de 2025.

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To quote as:

Guerrero-Beltrán, Y. L., L. C. Villanueva-Fonseca, A. M. Góngora-Gómez, A. Lugo-Armenta, J. A. Hernández-Sepúlveda, C. H. Sepúlveda & M. García-Ulloa. 2025. Morpho-biometric relationships and allometry of the "black clam" (*Anadara mazatlanica*) from two coastal lagoons in the southeastern Gulf of California. *Hidrobiológica* 35 (2): 97-107.

DOI:10.24275/CVUQ6350

ABSTRACT

Background. Phenotypic plasticity in bivalve mollusks, such as *Anadara mazatlanica* ("black clam"), is influenced by both external environmental and internal biological factors, which causes changes in the metric variables of the shell and in the relationship between them. **Goals.** This study examined the association of environmental variables with the biometric indices and morphometric relationships of *A. mazatlanica* collected from two sites in the southeastern Gulf of California from March 2022 to February 2023. **Methods.** Monthly, environmental variables of the water were obtained (temperature, dissolved oxygen, salinity, pH, organic matter, inorganic matter, total suspended solids and chlorophyll *a*); also every month, samples of 120 clams were taken from the El Colorado (ECL) and Navachiste Lagoon (NL) systems in Sinaloa, Mexico, to obtain the height, length, and width of the shell (mm). **Results.** The clams from ECL were significantly larger in length, but exhibited lower shell compactness and cupping compared to those from NL ($p < 0.05$). At both locations, morphometric equations for *A. mazatlanica* displayed a linear positive relationship, with negative allometry ($b < 1$). The most representative growth ratios were shell width/shell height for ECL ($R^2 = 0.80$) and shell width/shell length for NL ($R^2 = 0.78$). Temperature and salinity were negatively related to shell dimensions in both locations. **Conclusions.** Significant monthly and annual variations were observed in all morphometric variables between the two populations, indicating that *A. mazatlanica* experiences environmental stress but also exhibits resilience to local conditions. This is the first morpho-biometric analysis of the "black clam" in this region, providing valuable insights for the species management.

Keywords: Bivalves, environment, Mexico, morphometry, relative growth.

RESUMEN

Antecedentes. La plasticidad fenotípica en moluscos bivalvos, como *Anadara mazatlanica* ("almeja negra"), está influenciada tanto por factores ambientales externos como biológicos internos, lo que provoca cambios en las variables métricas de la concha y en la relación entre ellas. **Objetivos.** Este estudio examinó la asociación de las variables ambientales con los índices biométricos y las relaciones morfométricas de *A. mazatlanica* recolectadas en dos sitios en el sureste del Golfo de California desde marzo 2022 hasta febrero 2023. **Métodos.** Mensualmente, se obtuvieron las variables ambientales del agua (temperatura, oxígeno disuelto, salinidad, pH, materia orgánica, materia inorgánica, sólidos suspendidos totales y clorofila *a*); también cada mes, se recolectaron 120 almejas en las lagunas El Colorado (ECL) y Navachiste (NL), Sinaloa, México, para obtener la altura, longitud y ancho de la concha (mm). **Resultados.** Las almejas de ECL fueron significativamente más grandes en longitud, pero menos compactas y acopadas de la concha en comparación con las de NL ($p < 0.05$). En cada sitio de muestreo, las ecuaciones morfométricas para *A. mazatlanica* mostraron tendencia lineal y positiva, con alometría negativa ($b < 1$). Las relaciones de crecimiento más representativas fueron anchura de la concha/altura de la concha para ECL ($R^2 = 0.80$) y anchura de la concha/longitud de la concha para NL ($R^2 = 0.78$). La temperatura y salinidad se relacionaron negativamente con las dimensiones de la concha en ambos lugares. **Conclusiones.** Se observaron variaciones mensuales y anuales significativas en todas las variables morfométricas entre las dos poblaciones, lo que indica que *A. mazatlanica* experimenta estrés ambiental pero también muestra resiliencia a las condiciones locales. Este es el primer análisis morfo-biométrico de la “almeja negra” en esta región, lo que proporciona información valiosa para el manejo de la especie.

Palabras clave: Bivalvos, crecimiento relativo, medio ambiente, México, morfometría.

INTRODUCTION

As part of the eco-services that bivalve mollusks offer to the habitat where they reside, the characteristic of being used as indicators of the quality of the aquatic environment stands out; since they are capable of accumulating and retaining, in their tissue and shell, various compounds found in water, including contaminants produced by anthropogenic activities (Vaughn & Hoellein, 2018; Barus *et al.*, 2023; Sepúlveda *et al.*, 2023). Specifically, the exoskeleton of these organisms is considered as an archive that stores the environmental changes of their habitat (Carroll *et al.*, 2009); which respond by presenting variations in the color pattern, structure and shape of their shell (Fritz *et al.*, 2022).

The analysis of morphological variations and allometric patterns in bivalve mollusks, driven by environmental pressures such as climate change, ocean acidification, and anthropogenic impacts (e.g., industrial activities and urban development), is recognized as a critical approach for designing bio-monitoring and environmental management programs (Morán *et al.*, 2022; Schaefer *et al.*, 2022). Additionally, overfishing and predation of these invertebrates may induce ecological plasticity responses, wherein alterations in shell shape and growth patterns within one or more populations reflect the adaptive pressure exerted by these stressors (Stewart *et al.*, 2021).

The use of functional parameters of bivalve shells –elongation, compaction, and convexity (Sepúlveda *et al.*, 2024)– that relate their linear dimensions (length, height, and width) represents a valuable tool to evaluate changes in their shape, which, according to Zhao *et al.* (2017) and Telesca *et al.* (2019), are subject to the ionic composition of the water and the effect of waves and currents, among other factors. On the other hand, morphometry –linear and/or sigmoidal– is a simple and non-invasive field technique (Gaspar *et al.*, 2001) that is widely used to: determine the growth of schools or groups of aquatic organisms (Peixoto *et al.*, 2004), analyze fishery and aquaculture production data when it is only possible to obtain length measurements (Grizzle *et al.*, 2016), compare traits morphological and eco-phenotypic (linear dimensions and body weight) between populations of a single species located in different regions (Karakulak *et al.*, 2006), and establish morphotypes of a species that inhabits different localities (Chauhan *et al.*, 2024), among other applications.

The “black clam”, *Anadara mazatlanica* (Hertlein & AM String, 1943) (Bivalvia: Arcidae), is distributed from the Gulf of California to Peru (Coan & Valentich-Scott, 2012). The shell of this bivalve is trapezoidal in shape, it exhibits several channels on the outer surface and its periostracum is wide and hard. Normally, *A. mazatlanica* lives in the subtidal and intertidal zone of the estuary, buried in the muddy substrate of the mangrove strip, associated with its roots (Coan & Valentich-Scott, 2012). This clam represents a valued resource of economic importance for the coastal communities of the southeastern Gulf of California and supports a large part of the annual clam fishery known as “mule foot”. However, information about the biology and ecology of this species is scarce. Specifically, the shape of its shell and allometry in different coastal localities of the region has not been reported. Therefore, the present study aims to evaluate the biometric and morphometric indicators of the shell of *A. mazatlanica* from two coastal lagoons in the southeastern Gulf of California. It is expected to find differences in the shape of the shell and the relative growth of this clam governed by the conditions of each place.

MATERIALS AND METHODS

Sampling of *A. mazatlanica* clams was carried out in the El Colorado lagoon (ECL; 25°44›10.73” N, 109°18›56.94” W, municipality of Ahome) and the Navachiste lagoon (NL; 25°31›18.25” N, 108°47›03.93” W, municipality of Guasave), in the north-central portion of the state of Sinaloa, Mexico (southeast Gulf of California; Fig. 1). A total of 1,440 specimens of “black clam” (*A. mazatlanica*) (n = 120 per month) were collected from the intertidal zone beneath the roots of red mangrove (*Rhizophora mangle*) at each coastal site between March 2022 and February 2023. The clams were placed in 50 L plastic containers filled with seawater and transported to the laboratory for further analysis (Sotelo-Gonzalez *et al.*, 2020).

During each sampling event, the following environmental variables were recorded: water temperature and dissolved oxygen (DO) using an oximeter (YSI 55/12 FT, Ohio, USA); salinity was measured with a precision refractometer (ATAGO S/Mill refractometer), and pH was determined using a potentiometer (Hanna HI 8314, USA) (Sepúlveda *et al.*, 2023). Concentrations of organic matter (OM), inorganic matter (IM), and total suspended solids (TSS) were determined using the gravimetric method described by APHA (1995). Chlorophyll *a* (Chl–*a*) concentration was measured following the spectrophotometric technique of Strickland & Parsons (1972), applying the equations of Jeffrey & Humphrey (1975).

For each specimen, shell length (SL, the maximum distance between the anterior and posterior margins), shell height (SH, the maximum distance between the hinge and the farthest edge), and shell width (SW, the maximum distance across the thickest part of the two valves) were measured using a digital vernier caliper (Mitutoyo, CD-8” CS, mm). These measurements were used to calculate biometric indices: elongation (ELO, SH/SL), compaction (COM, SW/SL), and convexity (CON, SW/SH) (Sepúlveda *et al.*, 2024). Descriptive statistics, including mean, standard deviation, maximum and minimum values, and coefficient of variation, were calculated for SL, SH, and SW.

To evaluate the biometric indicators of the clam shell, outliers were eliminated by applying the Durbin-Watson test. The data did not show normality (Kolmogorov-Smirnov) and were analyzed with a Kruskall-Wallis’ test. The morphometric relationships between the different shell dimensions (SL/SH, SW/SL, and SW/SH) for *A. mazatlanica* from each site were estimated using the linear equation $Y = bX + a$; where Y and X = shell dimensions (SL, SH, and SW, mm), a = intercept of slope in the Y axis, and b = slope. Relative growth is considered isometric when the exponent $b = 1$. The goodness of fit of the data was analyzed with the correlation coefficient, R^2 (Sokal & Rohlf, 1995).

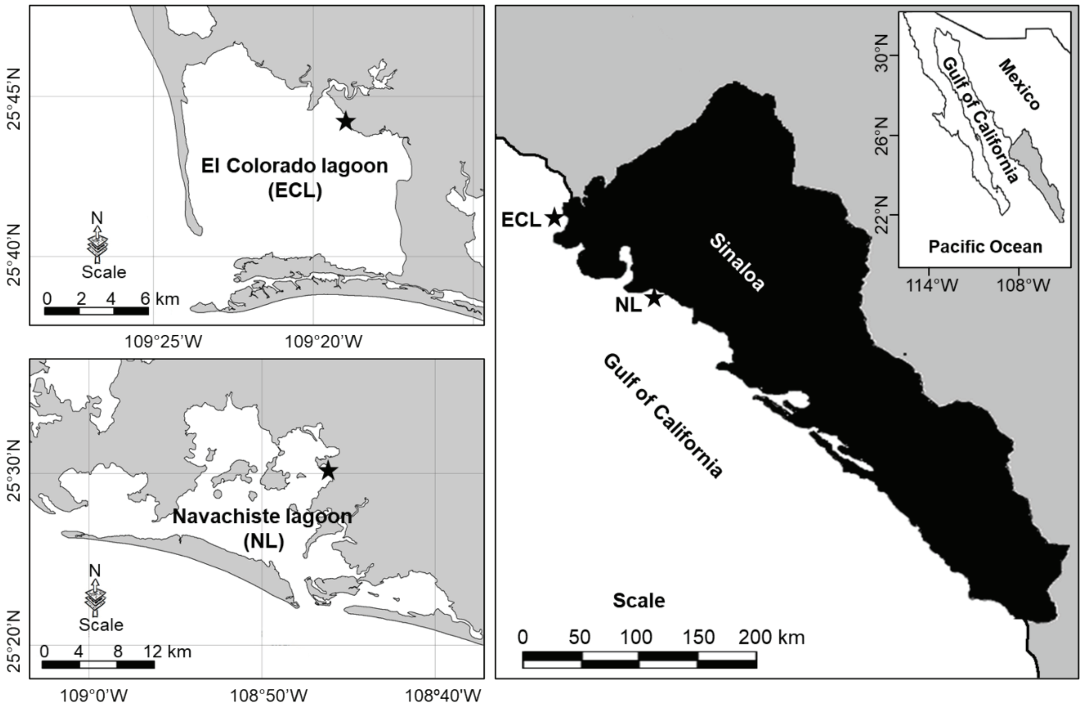

Figure 1. Location of the study area. El Colorado and Navachiste coastal lagoons (star) in the state of Sinaloa, Mexico (SE Gulf of California).

Clam size data from each sampling site were analyzed on a monthly and annual basis, with medians compared using the Kruskal-Wallis test. To assess differences between lagoons, the Mann-Whitney U test was applied. The Least Significant Difference (LSD) test was employed as a measure of goodness-of-fit, and Spearman's rank correlation coefficient (r) was used to examine the relationships between variables (Zar, 2010). Additionally, principal component analysis was conducted to identify the association between environmental variables and biometric and allometric indicators of clams from each coastal lagoon. Statistical analyses were performed using the Statgraphics Centurion XVI software (Statgraphics.Net, Madrid), with a 95% confidence level.

RESULTS

Among the environmental variables measured at the sampling sites, only temperature exhibited a clear annual seasonal pattern in both coastal lagoons, ranging from 18.73±0.80 to 31.33±0.11 °C in NL, and from 20.05±0.87 to 33.10±0.21 °C in ECL (measured in July 2022 and February 2023, respectively; Fig. 2). The lowest values for salinity, dissolved oxygen (DO), pH, organic matter (OM), inorganic matter (IM), suspended solid total (SST), and chlorophyll-*a* (Cl–a) were observed in ECL (13.50±0.70 ‰, March), NL (1.12±0.11 mg L^{-1}, July), NL (7.31± 0.00, June), ECL (5.14±0.71 mg L^{-1}, March), ECL (6.06±0.48 mg L^{-1}, March), ECL (11.19±2.35 mg L^{-1}, March), and ECL (0.39±0.07 mg m^{-3}, March), respectively. In contrast, the highest values were recorded in ECL (40.10±0.29 ‰, June), ECL (9.10±0.23 mg L^{-1}, June), NL (8.49±0.16, November), ECL (34.63±0.21 mg L^{-1}, July), ECL (167.32±2.58 mg L^{-1}, July), ECL (201.95±3.48 mg L^{-1}, July), and NL (26.32±0.36 mg m^{-3}, March), respectively (Fig. 2).

The biometric parameters of *A. mazatlanica* shells showed significant monthly differences within each coastal lagoon ($p < 0.05$; Table 1). The shell length (SL), shell height (SH), and shell width (SW) ranged from 31.7–91.2 mm, 27.2–67.8 mm, and 17.8–57.4 mm in ECL, and from 31.8–78.8 mm, 22.8–59.7 mm, and 20.6–46.9 mm in NL, respectively. Clams from ECL were consistently larger across all dimensions (SL = 54.8±7.4 mm, SH = 40.9±5.6 mm, SW = 30.9±5.3 mm). Except for the May–June 2022 period (and SL in January 2023), significant monthly differences ($p < 0.05$) were detected in biometric indices between the two lagoons (Table 1). Significant differences ($p < 0.05$) between the two clam populations were observed only for SL and SH.

Shell elongation, compaction, and convexity of the ""black clam"" exhibited significant monthly and annual differences ($p < 0.05$) between the two coastal lagoons (Table 2). Monthly comparisons revealed a variable pattern, with ELO, COM, and CON showing no significant differences only in August, October, November, and February. Annually, clams from NL had higher COM and CON values compared to those from ECL. However, ELO did not differ significantly between the two populations ($Z = 0.34$; $p > 0.05$).

The morphometric relationships of shell dimensions of *A. mazatlanica* showed a linear and positive trend in ECL and NL. The coefficient of determination (R2) in ECL ranged between 0.76 (*b* SW/SL) and 0.80 (*b* SW/SH); while, for NL, the lowest value ($R^2 = 0.72$) was obtained for *b* SW /SH and the highest ($R^2 = 0.78$) for the *b* SW/SL relationships (Fig. 3). The slope value (*b*) was less than 1 in all morphometric associations, denoting negative allometric growth in the clams from ECL and NL.

Water temperature and salinity showed, respectively, negative correlations with SL ($r = -0.83$, $p = 0.00$ and $r = -0.68$, $p = 0.03$), SH ($r = -0.76$, $p = 0.01$ and $r = -0.61$, $p = 0.04$), and SW ($r = -0.80$, $p = 0.00$ and $r = -0.59$, $p = 0.04$) of *A. mazatlanica* from NL and ECL. Only OM was positively correlated with *b* SL/SH ($r = 0.80$, $p = 0.01$) in NL.

Of the variances of all the variables analyzed (17) in the two sampling sites, the eigenvalues of five components satisfactorily explain the correlations of ECL (86.78%) and NL (88.84%). The points obtained in the principal components analysis in the two lagoons show different groupings of the biometric and allometric variables of the clams, in relation to the environmental variables (Fig. 4). The dispersion of the points for *A. mazatlanica* presented an interval of -5.17 to 5.01 in ECL and -4.12 to 3.44 in NL. In ECL, CON was associated with *b* SL/SW and *b* SH/SW). In both locations, COM was correlated with shell dimensions of *A. mazatlanica*.

DISCUSSION

It has been documented that the combined effects of environmental factors, such as temperature and ocean acidification (Martel *et al.*, 2022), along with anthropogenic activities (Stewart *et al.*, 2021), can alter the physiology underlying the phenotypic plasticity of the exoskeleton in calcifying aquatic species, such as bivalve mollusks. These changes may affect the shape, coloration, and composition of the shell. In this study, the observed temperature range was consistent with other reports for both study locations. For instance, Góngora-Gómez *et al.* (2020) recorded a temperature range of 18.8–33.3 °C in a culture of the "mangrove oyster" *Crassostrea corteziensis* near NL, while Góngora-Gómez *et al.* (2022) reported a range of 15.9–32.1 °C for the "venus clam" *Chionista fluctifraga* in an intertidal zone of ECL. However, our dissolved oxygen (DO) and salinity values differ from those reported by García-Ulloa *et al.* (2023) for NL (<5 mg L^{-1}) and ECL (35–42 ‰), and from Villanueva-Fonseca *et al.* (2020) for the pH in NL (7.03), who studied the mussel *Mytella strigata* and *C. corteziensis*, respectively.

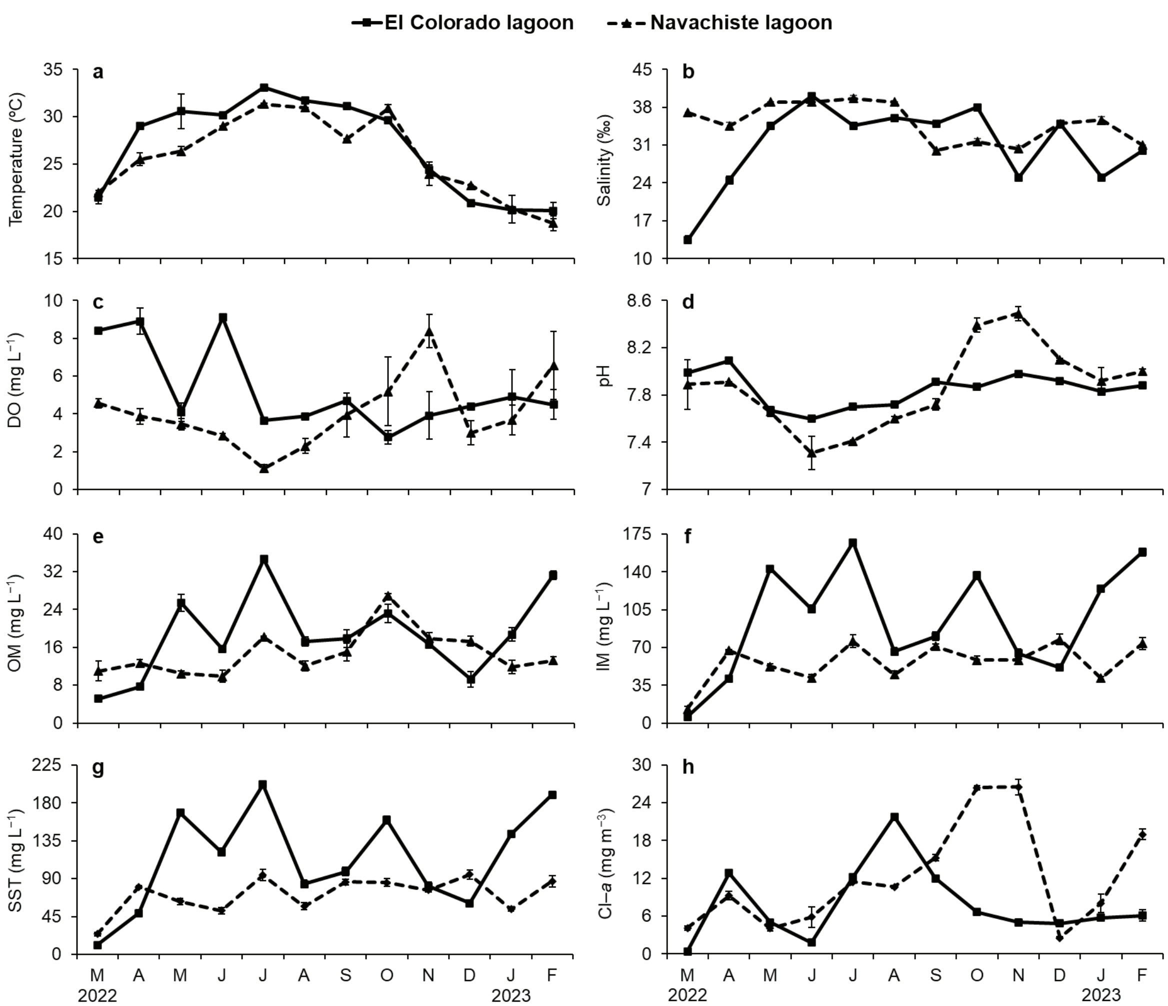

Figure 2. Environmental variables in the sampling sites. a) Temperature; b) Salinity; c) Dissolved oxygen (DO); d) pH; e) Organic matter (OM); f) Inorganic matter (IM); g) Total suspended solids (TSS); h) Chlorophyll *a* (Cl–*a*).

Table 1. Monthly comparison (mean ± standard deviation; $n = 120$) of the biometric parameters of the shell of *A. mazatlanica* from the El Colorado (ECL) and Navachiste (NL) lagoons, and between the two localities.

Months of	Shell length (mm)			Shell height (mm)			Shell width (mm)		
sampling	ECL	NL	*Z*	ECL	NL	*Z*	ECL	NL	*Z*
M 2022	$59.6{\pm}8.3^{f}$	$56.7{\pm}4.9^{fg}$	2000*	$44.3{\pm}6.5^{g}$	$43.8{\pm}4.1^{ef}$	977*	$33.5{\pm}5.7^{f}$	$32.8{\pm}3.7^{de}$	-1055*
A	$56.7{\pm}6.5^{de}$	$52.4{\pm}4.6^{bc}$	3084*	$41.3{\pm}5.0^{def}$	$38.3{\pm}4.2^{c}$	2743*	$31.4{\pm}4.7^{de}$	$29.6{\pm}3.2^{b}$	-2012*
M	$55.4{\pm}6.4^{cde}$	$54.0{\pm}6.3^{def}$	963	$41.0{\pm}5.1^{de}$	$41.4{\pm}5.0^{e}$	-376	$31.3{\pm}4.5^{de}$	$31.7{\pm}5.1^{cde}$	397
J	$54.3{\pm}6.4^{c}$	$53.2{\pm}5.8^{cde}$	899	$40.1{\pm}4.7^{cd}$	$39.5{\pm}4.4^{d}$	638	$30.0{\pm}4.4^{c}$	$30.7{\pm}4.1^{c}$	814
J	$54.4{\pm}5.3^{c}$	$50.5{\pm}5.3^{a}$	3161*	$38.9{\pm}3.7^{bc}$	$35.6{\pm}3.8^{a}$	-3673*	$30.8{\pm}3.8^{cd}$	$28.4{\pm}3.9^{a}$	-2753*
A	$54.9{\pm}6.2^{cd}$	$50.9{\pm}4.7^{a}$	3021*	$41.2{\pm}4.4^{def}$	$38.3{\pm}3.5^{c}$	-2845*	$31.1{\pm}4.3^{cde}$	$28.3{\pm}3.5^{a}$	-2843*
S	$50.4{\pm}5.0^{b}$	$52.5{\pm}4.4^{bcd}$	-1974*	$38.6{\pm}4.4^{b}$	$39.8{\pm}3.3^{d}$	1426*	$27.7{\pm}3.8^{b}$	$29.6{\pm}3.1^{b}$	2422*
O	$56.4{\pm}5.8^{de}$	$51.3{\pm}5.5^{ab}$	3733*	$42.3{\pm}4.3^{f}$	$38.2{\pm}4.1^{c}$	-3924*	$31.8{\pm}3.9^{de}$	$28.6{\pm}3.8^{ab}$	-3408*
N	$57.0{\pm}9.3^{e}$	$51.3{\pm}5.1^{ab}$	2898*	$44.1{\pm}7.1^{g}$	$39.5{\pm}4.9^{d}$	-2837*	$33.2{\pm}6.8^{f}$	$29.25{\pm}3.7^{ab}$	-2588*
D	$48.1{\pm}4.5^{a}$	$55.5{\pm}7.5^{g}$	-4378*	$35.5{\pm}3.4^{a}$	$41.9{\pm}6.1^{e}$	4409*	$26.0{\pm}2.8^{a}$	$32.6{\pm}5.41^{ef}$	5130*
J 2023	$55.6{\pm}9.4^{cde}$	$54.3{\pm}7.1^{efg}$	775	$42.2{\pm}7.0^{ef}$	$39.8{\pm}4.6^{d}$	-1699*	$33.1{\pm}7.4^{f}$	$30.9{\pm}4.9^{cd}$	-1398*
F	$55.7{\pm}7.1^{cde}$	$57.9{\pm}6.5^{h}$	-1396*	$42.0{\pm}5.2^{ef}$	$43.2{\pm}5.0^{f}$	1113*	$32.2{\pm}5.1^{ef}$	$33.4{\pm}4.6^{f}$	1277*
Overall mean	54.8±7.4	53.3±6.1	-133211*	40.9±5.6	39.9±5.0	-110478*	30.9±5.3	30.5±4.5	-55299
Máximo	91.2	78.8		67.8	59.5		57.4	46.9	
Maximum	31.7	31.8		27.2	22.8		17.8	20.6	
CV	13.5	11.5		13.8	12.4		17.2	14.7	

Z = U Mann Whitney value; CV = coefficient of variation. Columns (biometric parameter) with different superscript letters denote significant differences ($p < 0.05$) among sampling months. *Z* values with an asterisk denote significant differences ($p < 0.05$) among the monthly-annual mean of the biometric parameter of between the two localities.

Although the two coastal lagoons are located 67 km from each other, the differences in DO, salinity, and pH can be explained by factors inherent to their latitude (Beukema & Meehan, 1985), such as the residence time of the particles due to the intensity of the tides (Takasu *et al.*, 2020), the interaction of trophic levels of each habitat (Hope *et al.*, 2020), the influence of freshwater contributions –such as rivers and lagoons– to the estuaries (Ringwood & Keppler, 2002), and the anthropogenic activities that take place, both in the aquatic body and in its surroundings (Sepúlveda *et al.*, 2023). The NL (14,000 ha) is part of the San Ignacio-Navachiste-Macapule lagoon complex, which, despite being classified as a protected natural area (RAMSAR site # 1826), is surrounded by shrimp farms (21,709 ha), plots agricultural (124,287 ha), and urban and industrial areas (≈ 289,370 inhabitants) that produce organic and chemical waste that are discharged into channels that flow towards the lagoon. In the case of ECL (11,500 ha) –it is part of the Agiabampo-Bacorehuis-Río Fuerte Antiguo lagoon system– it receives contributions from the Fuerte River through wastes from the annual production of pigs (≈ 94,422), chemicals used in 15,947 ha of shrimp, agricultural and urban sewage derived, respectively, from 214,455 ha and from a population of more of 459,310 inhabitants, and from the fishing activity in the region (INEGI, 2020; CESASIN, 2022; Sepúlveda *et al.*, 2023; SIAP, 2023).

The results of the environmental variables combined with the specific industrial and urban development of each lagoon would partially explain the differences found in the shell shape and allometry of *A. mazatlanica*. For instance, temperature and salinity presented a similar behavior throughout the study year –with the highest values from March to September– showing a negative correlation ($p < 0.05$) with shell dimensions in the two clam communities. It is well documented that these two environmental factors are strongly involved in growth of mollusks (Lee *et al.*, 2024). In fact, low temperatures induce the increase of primary production (Murphy *et al.*, 2016) which promoted shell growth of clams; meanwhile, the recorded salinity fluctuation (13-40 ‰) could have had a negative effect on the dimensions of the shell of *A. mazatlanica* in both locations, which coincides with Dai *et al.* (2023) for the clam *Mactra chinensis*. These authors argued that water salinity can be dramatically altered by freshwater inputs such as rivers, rainfall and irrigation canals, a similar situation found in the two areas of the present study. Another aspect that needs to be considered is the recurrent presence of upwellings in the area (Pérez-Quiñonez *et al.*, 2018), which carry nutrients from the seabed to the surface. On other hand, Fisher *et al.* (1995) mention that the maximum shell length for this species is up to 75 mm, but commonly, it is found to be 50 mm; size that coincides with the average length of the "black clam" in the two populations studied, and with that reported by these authors for another clam of the Arcidae family (*Anadara similis*), with which *A. mazatlanica* is usually confused. Manjarrés-Villamil *et al.* (2013) studied the sexual maturation and reproduction of *A. similis*, observing adult organisms in reproduction with an average length of 41.8±4.5 mm. Therefore, it can be inferred, in the absence of specific information for *A. mazatlanica*, that the clams collected in this study –larger than 50 mm– were adult organisms. The histological analysis of the specimens in our laboratory (in progress) will complement the previous information.

SL, SH, and SW presented monthly and annually differences for each population of the “black clam”. The largest clams were found in ECL, which can be associated with the quantity and quality of the anthropic contributions (organic and inorganic) of this locality (SIAP, 2023), as well as the low fishing effort in this lagoon –compared to the larger fishing population in NL (SIAP, 2023)–, allowing bigger clam size. The latter coincides with Dalgiç *et al.* (2010) who found that fishing pressure affected both the size structure and maximum size of the clam *Chamelea gallina* on the Black Sea coast, Turkey. The same size-fishing effort effect was observed by Elvira & Jumawan (2017) and Bersaldo *et al*. (2023) for the mud clam *Polymesoda erosa* and the mangrove clam *Pegophysema philippiana*, respectively. However, the use of a single dimension in the shell of bivalves –usually length– is not a reliable tool to evaluate their growth and development (Caill-Milly *et al.*, 2012); therefore, it is advisable to use functional and morphometric parameters that use values related to two shell dimensions.

Clams from NL –although smaller in SL– showed a slightly more compact (SW/SL) and cupped (SW/SL) shell ($p < 0.05$), but equally elongated (SH/SL) than those from ECL. Uba (2021) mentions that bivalves with greater shell convexity suggest that the organism has more intravalvar capacity, possibly associated with tissue growth, whether reproductive or somatic. The variation in the shell shape of different bivalve mollusks has been related to the effect of biotic (genetic, biological associations, food availability, reproduction; Richard & Prezant, 2021) and abiotic (natural and anthropogenic; Fitzer *et al.*, 2015) factors and their interrelationship (Shields *et al.*, 2008). Specifically, Harayashaki *et al*. (2020) reviewed the effect of chemical contaminants on 26 species of mollusks in different parts of the world, detecting alterations in the shape and matrices –organic and inorganic– of their shell according to the degree of contamination, which, combined with the different anthropogenic activities in each locality, could partially explain the differences between the two clam populations studied. However, there is no punctual information about the factors that cause variation in the shell shape of *A. mazatlanica*, which highlights the importance of the present study.

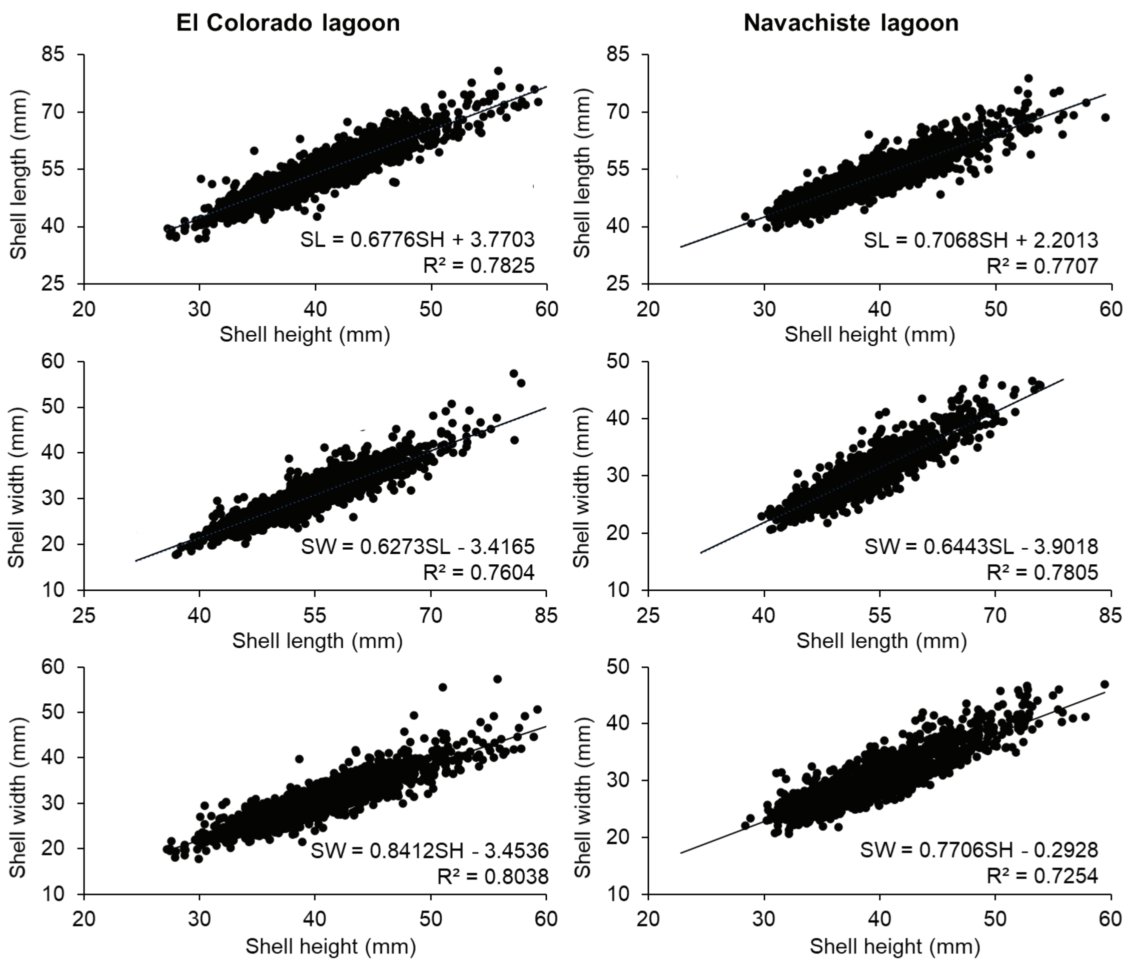

Figure 3. Morphometric relationships ($n = 1440$ clams per lagoon) among the shell dimensions of *A. mazatlanica* sampled in two lagoons (El Colorado and Navachiste) from the southeast Gulf of California. R^2 = coefficient of determination.

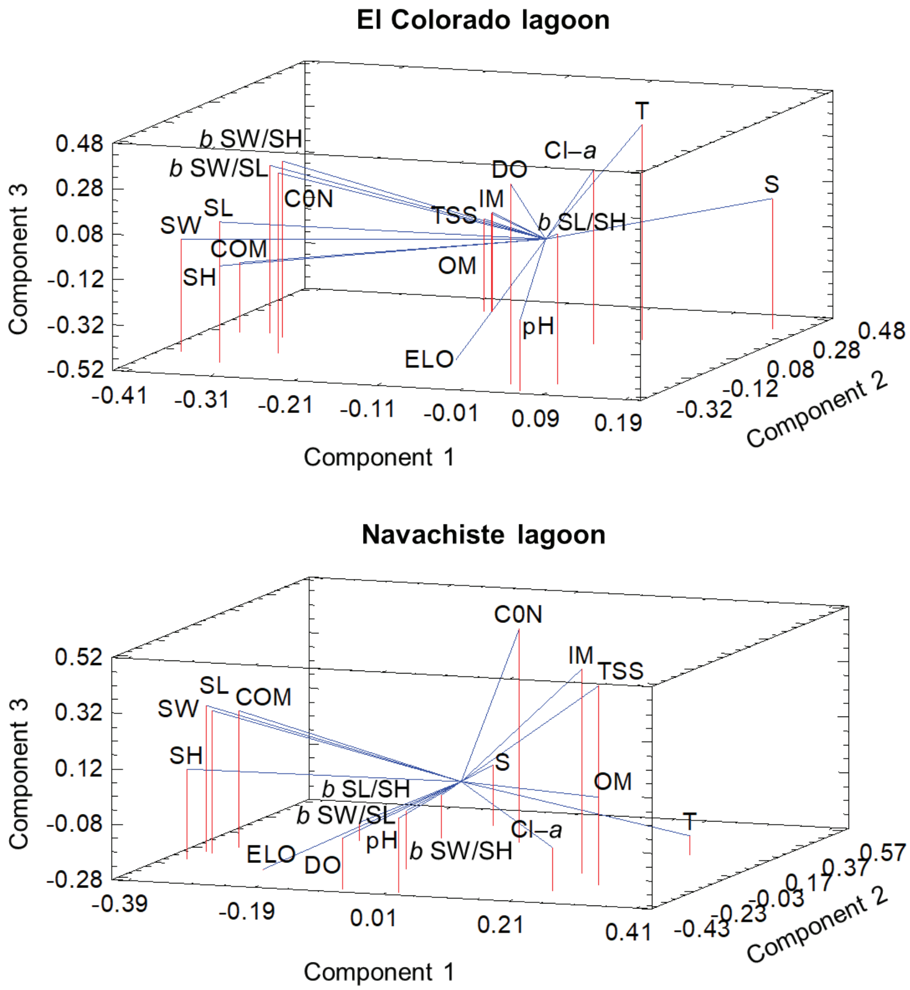

Figure 4. The principal component analysis of *A. mazatlanica* in the El Colorado and Navachiste lagoon. T = temperature; S = salinity; DO = dissolved oxygen; pH = pH units; OM = organic matter; IM = inorganic matter; TSS = total suspended solids; Cl–*a* = chlorophyll *a*; SL = shell length; SH = shell height; SW = shell width; ELO = shell elongation; COM = shell compactness; CON = shell convexity; *b* SL/SH = shell length/height relationship; *b* SW/SL = shell width/length relationship; *b* SW/SH = width/height relationship.

The regression equations for the morphometric associations of the shell dimensions –SL/SH, SW/SL, and SW/SH– of *A. mazatlanica* from the two lagoons were linear and allometrically negative ($b < 1$), which suggests little proportionality in growth between SL, SH, and SW. Gaspar *et al.* (2002) and Thomas (2013) mention that the negative allometric development found in the Mediterranean clams, *Donax trunculus* and *Acanthocardia pausicostata*, and in the short-necked clam *Paphia malabarica*, respectively, was related to the presence of organisms that preferentially live buried in the sediment –without exposure to waves– attributing it to an adaptive protection strategy, which coincides with the habitat where *A. mazatlanica* is found. In the same way, Degamon *et al.* (2023) mentions that the negative allometric pattern in different molluscs species indicates that shell length increases faster than total weight, which is characteristics of organisms inhabiting mangrove ecosystems. According to Ríos-Jara *et al.* (2019), the negative allometric growth found in the clam *Donax punctatostriatus* is typical of adult organisms –sexually mature and slower growth– that, firstly, ensure recruitment and secondly, present a more compressed shell shape that facilitates a rapid burying behavior in the sand for escaping of predators. These traits can also be attributed to the *A, mazatlanica* populations studied. By lagoon, the highest coefficients of determination (R^2, ECL = 0.80, NL = 0.78) indicate a moderate allometric proportion, whose most appropriate morphometric relationship –to describe its growth– is different for each population (SW/SH for ECL and SW /SL for NL).

Sotelo-Gonzalez *et al.* (2020) reported the SW/SH ratio as the most appropriate to describe the relative growth of *Larkinia grandis* (Arcidae), coinciding with the population of the “black clam”, both in NL. The above reinforces the argument of the effect of the environmental conditions of the place on the shape of the shell in these arcid clams. Again, the differences between the allometry of *A. mazatlanica* of the two populations studied could be attributed to internal factors (sexual maturity, age, metabolism, etc., Turra *et al.*, 2018) or external factors (environmental variables and anthropogenic activities of each locality, Pouil *et al.*, 2021).

Table 2. Monthly comparison (mean ± standard deviation; $n = 120$) of the biometric indexes of the shell of *A. mazatlanica* from the El Colorado (ECL) and Navachiste (NL) lagoons, and between the two localities.

Months of	Elongation			Compactness			Convexity		
sampling	ECL	NL	*Z*	ECL	NL	*Z*	ECL	NL	*Z*
M 2022	0.74±0.03^{cd}	0.77±0.03^{f}	6.10*	0.56±0.04^{bcd}	0.57±0.04^{cd}	2.60*	0.75±0.05^{bc}	0.75±0.04^{a}	-1.49
A	0.72±0.03^{ab}	0.73±0.05^{b}	0.41	0.55±0.04^{bcd}	0.57±0.04^{abc}	2.41*	0.75±0.04^{bc}	0.78±0.06^{cd}	2.40*
M	0.74±0.05^{bc}	0.77±0.03^{f}	4.74*	0.56±0.05^{de}	0.59±0.04^{ef}	2.99*	0.76±0.05^{c}	0.76±0.06^{bc}	-0.07
J	0.75±0.05^{bc}	0.74±0.04^{cd}	0.35	0.55±0.04^{abc}	0.58±0.03^{de}	4.93*	0.74±0.04^{b}	0.78±0.05^{cd}	5.01*
J	0.71±0.03^{a}	0.71±0.02^{a}	-3.02*	0.56±0.03^{de}	0.56±0.04^{ab}	-0.08	0.79±0.04^{d}	0.80±0.06^{e}	1.18
A	0.75±0.03^{cdef}	0.75±0.04^{de}	0.50	0.56±0.03^{de}	0.56±0.04^{a}	-2.00	0.75±0.04^{bc}	0.74±0.07^{a}	-1.88
S	0.76±0.04^{f}	0.76±0.03^{e}	-1.58	0.54±0.04^{ab}	0.56±0.03^{ab}	2.60*	0.71±0.05^{a}	0.74±0.03^{a}	3.79*
O	0.75±0.03^{cde}	0.75±0.03^{de}	-1.15	0.56±0.03^{cd}	0.56±0.04^{a}	-1.16	0.75±0.04^{bc}	0.75±0.05^{ab}	-0.43
N	0.77±0.09^{g}	0.77±0.05f	-0.97	0.58±0.08^{fg}	0.57±0.03^{bcd}	-1.53	0.74±0.07^{b}	0.74±0.07^{a}	-0.63
D	0.73±0.03^{bc}	0.76±0.05^{de}	2.94*	0.53±0.03^{a}	0.59±0.07^{g}	6.98*	0.73±0.03^{a}	0.78±0.08^{d}	6.24*
J 2023	0.76±0.06^{ef}	0.74±0.04^{bc}	-4.11*	0.59±0.07^{g}	0.57±0.03^{bcd}	-3.61*	0.77±0.06^{d}	0.77±0.06^{cd}	-0.59
F	0.75±0.07^{def}	0.75±0.05^{def}	-1.03	0.57±0.07^{ef}	0.58±0.04^{de}	-0.21	0.74±0.06^{c}	0.77±0.07^{bc}	1.12
Overall mean	0.74±0.04	0.75±0.06	0.34	0.55±0.04	0.57±0.05	3.39*	0.71±0.06	0.76±0.06	3.68*

Z = U Mann Whitney value. Columns (biometric indexes) with different superscript letters denote significant differences ($p < 0.05$) among sampling months. Z values with an asterisk denote significant differences ($p < 0.05$) among the monthly-annual mean of the biometric indexes of between the two localities.

Axes 1 and 2 of the principal component graphs in the two sampling sites did not show that environmental variables exert a determinant effect on the biometric indicators or on the allometric growth of the clam. In ECL, allometric growth variables and shell dimensions are negatively related to principal components 1 and 3; meanwhile most environmental variables are indistinctly oriented toward components 1 and 2. On the contrary, in NL the dimensions of the shell and COM are outlined in component 3, while the rest of the variables are distributed in components 1 and 2 without a clear grouping. Rather, COM clustered with shell dimensions in the two populations and, specifically in ECL, CON was also associated with allometric growth (*b* SL/SW; *b* SH/SW) of *A. mazatlanica*. Moreover, there is information that links more specific external factors to the development of arcid clams. For example, Debenay *et al.* (1994) observed that the growth of the clam *Anadara senilis* –in Senegal– decreased after summer rains, but even more so during winter. On the other hand, Broom (1982) concluded that density and air exposure were the main factors that affected the growth of natural and cultivated seeds of *A. granosa*. With this same species, Komala and Zahara (2021) documented that the most prominent parameters that affect the dimensions of its shell are nitrogenous compounds (ammonia and nitrites) and some metals (lead, cadmium and mercury), among others. In this study, temperature and salinity showed negative associations with shell dimensions, coinciding with what was reported by Wang *et al.* (2017) for *Anadara broughtonii* juveniles, and only OM presented a direct effect on *b* SL/SH ($r = 0.80$, $p = 0.01$) in the *A. mazatlanica* population of NL. The difference between previous works could be due to the environmental conditions and anthropogenic activities of each place and the species, mainly.

Despite the proximity of the studied localities, the populations of *A. mazatlanica* showed differences in the dimensions of their shell, functional parameters (ELO, COM, and CON), and allometry. Therefore, we conclude that the effect exerted by the environmental conditions and anthropogenic activities of each place is responsible for the presence of two possible morphotypes of the clam. This species demonstrates its phenotypic plasticity as a resilience strategy under the pressure of environmental changes in the region. The comparative biological measurements obtained for the two populations of the "black clam" represent essential tools to analyze conservation and management strategies of the resource and contribute to generating information for this species in the area.

ACKNOWLEDGMENTS

The authors thank the National Polytechnic Institute (IPN), through the project SIP-20230821 (Presence of *Perkinsus marinus* in the mule foot clam *A. mazatlanica* from two lagoons in the southeastern Gulf of California), for the economic and logistical support to carry out this research. YLGB and ALA thank the IPN research direction for the BEIFI scholarship, awarded to support their research.

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