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Research Article

Distribution, abundance, growth, and survival of juveniles of *Penaeus* (*Farfantepenaeus*) *aztecus* in Laguna Larga, in the southwest of the Gulf of Mexico

Sergio Cházaro-Olvera[1], Andrea Citlali Morales-Olguin[1], Ángel Morán-Silva[2]
Jesús Montoya-Mendoza[3], Rafael Chávez-López[2] & Jorge Montoya-Benítez[1]
[1]Laboratorio de Crustáceos, Facultad de Estudios Superiores Iztacala
Universidad Nacional Autónoma de México, Tlalnepantla, Estado de México, México
[2]Laboratorio de Investigación de Acuícola Aplicada, Tecnológico Nacional de México
Instituto Tecnológico de Boca del Río, Boca del Río, Veracruz, México
[3]Laboratorio de Ecología Costera y Pesquerías, Facultad de Estudios Superiores Iztacala
Universidad Nacional Autónoma de México, Tlalnepantla, México
Corresponding author: Sergio Cházaro-Olvera (schazaro@gmail.com)

ABSTRACT. The present study aimed to evaluate the distribution, abundance, growth, and survival of juvenile of the brown shrimp *Penaeus* (*Farfantepenaeus*) *aztecus* Ives, 1891 in Laguna Larga. The shrimps were collected by trawling on submerged vegetation with a Renfro-type net. Juveniles were fixed in 96% alcohol and transported to the laboratory, where they were measured and weighed. Temperature, salinity, dissolved oxygen, total dissolved solids, and pH were measured *in situ*. The highest values were as follows: dissolved oxygen 6.23 ± 0.45 mg L^{-1}, pH 8.17 ± 0.09, temperature 30.79 ± 1.51°C, dissolved solids 87.43 ± 11.20 ppt, and salinity of 32.78 ± 1.43. A total of 1,739 juveniles were collected, with the highest number in August. Four to six age classes were obtained. The bent-line and Gompertz models provided the best fit to the growth data. The maximum length evaluated for juveniles was 65.79 ± 0.71 mm. The model of relationship temperature growth rate was 3.2 to 4.4 mm $week^{-1}$. Growth patterns were positively allometric. Survival rate was 13.71%. According to the generalized linear model analysis, pH, temperature, and salinity were significantly related to species abundance across sampling months. The body growth rates of juveniles of this species were closely related to rising water temperatures. The highest mortality rates and, consequently, the lowest survival rates were observed in June and August, establishing a trade-off with growth, as these months saw a high rate of size increase.

Keywords: Penaeoidea; brown shrimp; population; aquatic environment; estuary; Mandinga Lagoon System

INTRODUCTION

Species with complex life cycles migrate throughout their life cycles, occupying various habitats during different developmental stages. The shrimp genus *Penaeus* plays a key role in food webs (Mace & Rozas 2018) and supports valuable fisheries (Rezek et al. 2022). After the planktonic mysis stage, they recruit to estuaries, where they shift to the benthic habitat and transform into juveniles (Duun et al. 2025).

From an adaptive perspective, the transport of larvae by surface currents is advantageous for anadromous species because it enables populations to interbreed and colonize new areas. The transport of penaeid shrimp larvae and postlarvae involves selective mechanisms driven by tides, salinity changes (Hughes

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1969), endogenous changes (Hughes 1972), and hydrostatic pressure (Forbes & Benfield 1991). On the other hand, during the transport of postlarvae, active movements of larvae, such as vertical migration (Rothlisberg et al. 1983, Wenner et al. 1998), are combined with changes in water temperature in the coastal zone, such as the estuaries, salinity changes, and current direction (Hughes 1969, Rogers et al. 1993).

Estuaries are among the most important aquatic ecosystems globally. They are present in all coastal regions and serve as the interface between continental hydrological basins and the ocean, through which nutrients are transported that are integrated into estuarine food chains. They also export energy that benefits coastal food chains, where the postlarvae and juveniles of brown shrimp play an essential role (Abrantes & Sheaves 2010). In addition, estuaries function as zones of recruitment, protection, feeding, growth, and development of species such as penaeid shrimp (Jordan & Peterson 2012).

Growth and survival are two life-history patterns that define population structure (Begon et al. 1998). For analysis, crustacean growth must be considered discontinuous, occurring in a "step-like" manner (Chang et al. 2012). Measuring organisms of various sizes in samples from the population allows us to relate length changes to their respective frequencies and to resolve the problem of missing growth marks (Gulland & Rosenberg 1992). Certain mathematical models, such as Bhattacharya's (1967), separate frequency curves by assuming that the tips of these curves represent different age classes (Pauly 1983). On the other hand, growth models such as von Bertalanffy (VB), Gompertz, and logistic are often used to obtain growth parameters (Chang et al. 2012). Thus, after determining the age classes, we can calculate the number of individuals in each class, followed by an evaluation of mortality and survival (Ricker 1975).

The brown shrimp *Penaeus* (*Farfantepenaeus*) *aztecus* occurs along the western Atlantic coast from Martha's Vineyard, Massachusetts, USA, through Florida and the Gulf of Mexico, to the lower Yucatan Peninsula (Williams 1984). The brown shrimp is a species of great importance in the Gulf of Mexico, mainly in the states of Tamaulipas, Veracruz and Campeche, since it is the main support of the shrimp fishery in this region and by representing 95% of the total catch of the shrimp resource (Wakida-Kusonoki et al. 2006), between 2014 and 2023 of 13,357 to 23,483 t have been obtained (Comisión Nacional de Acuacultura y Pesca 2024).

Studies on migration, distribution, recruitment, and abundance of postlarvae and juveniles of this species in the Gulf of Mexico include those by Castro-Meléndez et al. (1990), Barton et al. (1993), Sánchez & Soto (1993), Leija-Tristán et al. (1995), Barba-Macías (1999), Ocaña-Luna (2008), and Rodríguez-Varela et al. (2025), who studied distribution and abundance of the mysis stage of penaeid in the Mandinga Lagoon System. Analyses of population characteristics for growth and survival have already been developed for adults; therefore, the present study aims to evaluate the distribution, abundance, growth, and survival of brown shrimp juveniles in Laguna Larga, in the southwestern Gulf of Mexico.

MATERIALS AND METHODS

Study area

The Mandinga System Lagoon, located in the municipality of Alvarado, Veracruz, Mexico, lies between 19°00'-19°06'N and 96°02'-96°06'W, oriented north-south. Approximately 20 km in length, the system comprises six bodies of water: Estero El Conchal, which connects the system to the ocean via the Gulf of Mexico, Laguna Larga, Estero Horcones, Laguna la Redonda, Estero de Mandinga, and Laguna de Mandinga (Rodríguez-Varela et al. 2022). The climate is warm and subhumid. Cold fronts occur from October to March and are anticyclonic currents of cold winds that enter the Gulf of Mexico from North America (Ojeda et al. 2017). The dry season is from May to June, and rainfall is scarce. Finally, the rainy season lasts from July to September, when temperatures and precipitation increase (Zavala-Hidalgo et al. 2006). During the rainy season, precipitation ranges from 1,400 to 1,700 mm, while during the dry season, it ranges from 125 to 200 mm. Temperatures during the dry season range from 18 to 27°C, while during the rainy season, temperatures range from 22.5 to 33°C. The average annual temperature is above 22°C, and the lowest temperature recorded in the coldest month is above 18°C. The predominant vegetation in the area is mangroves, mainly along the lagoon's margin and on the artificial islands within it. The total area occupied by mangroves is estimated at approximately 428 ha (Paniagua-Cano et al. 2018).

Fieldwork

The organism collection took place in April, June, August, October, and December 2023, and in February 2024. A Renfro-type conical net measuring 1 m wide, 0.80 m high, 1 m cone length, and 330 µm mesh size (Cházaro-Olvera et al. 2017) was used at four stations along Laguna Larga (Fig. 1). The Renfro net was used

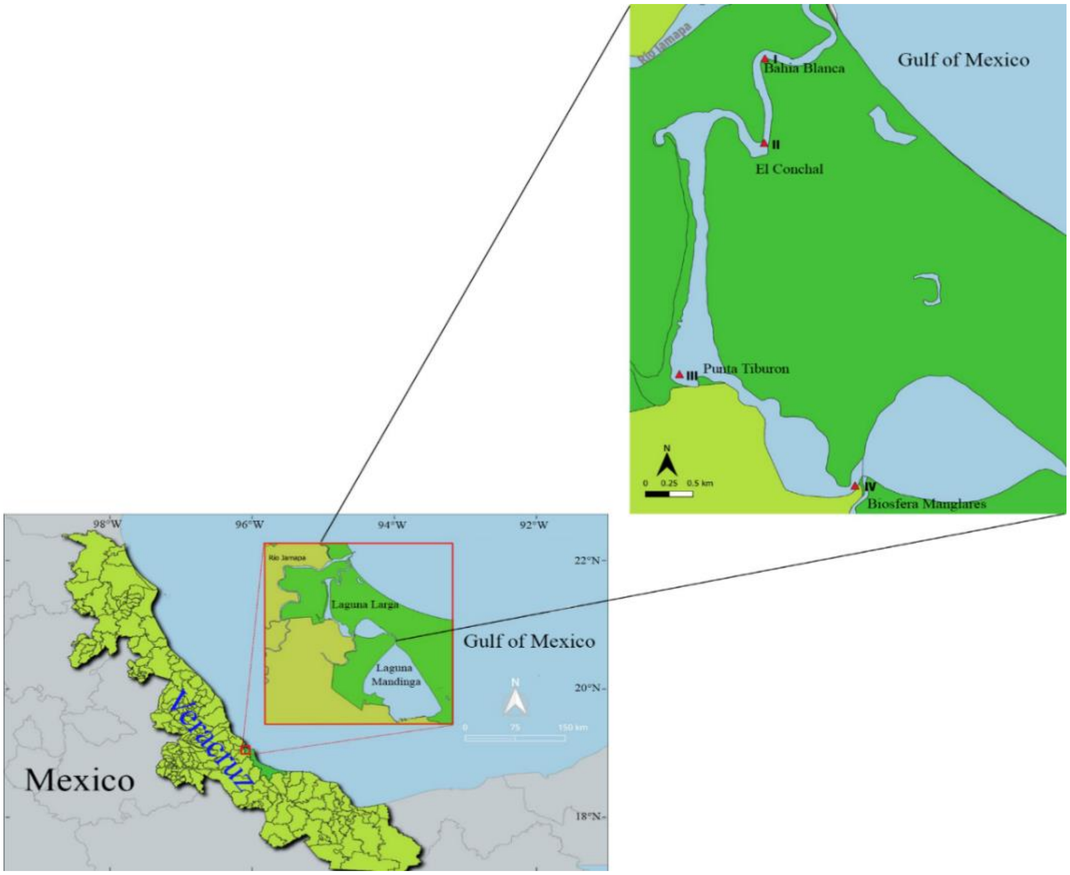

Figure 1. Study area with sampling sites in Laguna Larga belonging to the Mandinga Lagoon System, Veracruz, Mexico.

to perform trawls over the submerged vegetation of marine phanerogams *Ruppia maritima*; considering a net width of 1 m and a sweep distance of 10 m, the swept area covered was 10 m^2 at each sampling point.

Sample collection took place in the early morning, between 8:00 and 11:00 h. Living organisms were collected at each station and fixed *in situ* in 96% alcohol in jars labeled with site, date, season, and substrate type. During this phase, the physical and chemical factors of temperature (°C), salinity, dissolved oxygen (mg L^{-1}), total dissolved solids (ppt), and pH were measured in situ at a depth of 0.50 m using a Hanna HI9828® multiparameter equipped with HI769828DO® and HI769828PH® probes.

Laboratory work

The biological material was transported to the Crustacean Laboratory at FES-Iztacala-UNAM, Mexico, where the juvenile samples were separated using entomological needles under a Motic SMZ-168 stereomicroscope.

There, brown shrimp juveniles were identified and separated using the criteria of Pérez-Farfante (1970) and Williams (1984). Following this, each organism was measured. For the smallest specimens, length was measured in millimeters using a stereoscopic microscope, a high-resolution 5.0 MP microscope camera, and image viewer software. These instruments were calibrated using a micrometer ruler, with the calibration varying with magnification. Larger organisms were measured using a digital vernier caliper with a resolution of 0.2 mm. Finally, the weight of each specimen was obtained using an HR-120 Analytical Balance (Orion Series, A&D Brand), with a capacity of 120 g and a resolution of 0.0001g.

Statistical analysis

The relationship between shrimp density at sites and sampling months was analyzed in ecological studies using a generalized linear model (GLM) with a multinomial distribution. It allows modeling of relative abundance as a function of environmental predictors, where β is the contribution of each variable to the model. Each parameter was incorporated into the model as a covariate. Subsequently, the significance was obtained for each parameter analyzed ($P < 0.05$) (Roback & Legler 2021).

The generalized least squares (GLS) model was used to compare temperature (°C), salinity, and dissolved oxygen (mg L^{-1}) in the cold front, dry, and rainy seasons during five months of sampling at four sites (Zuur et al. 2007). The GLS analysis was performed using SPSS v. 25. To evaluate whether changes in species density depend on climatic conditions and sampling areas, a two-way factorial design was applied. Sites and climatic seasons were considered as fixed orthogonal factors. To compare abundance data across sites and months, the data were normalized using the natural logarithm to reduce skewness and stabilize variance; subsequently, ANOVA was applied (Magurran & Henderson 2003).

To analyze growth, the Bhattacharya (1967) method was applied to determine the number of age groups (cohorts, or modal groups) and their average lengths (Pauly & Caddy 1985).

The average lengths of each modal class were validated using the separation index (SI) of Sparre & Venema (1997):

$$SI = 2 \text{ x } ((Li_1 - Li_2) / (SDi_1 + SDi_2))$$

where Li_1 is the average length of cohort 1, Li_2 is the average length of cohort 2, SDi_1 is the standard deviation of cohort 1, and SDi_2 is the standard deviation of cohort 2.

To obtain the values of the growth parameters (K, t_0, L_{max}), the ELEFANT models and modal progression analysis of FISAT II were used (Gayanilo et al. 2005). Once the average lengths (dependent variable) of each class of size (independent variable or age relative 1, 2, 3, etc.) and initial parameters of growth were obtained, they were analyzed using the growth models from VB, Gompertz, logistics, and bent line (Chang et al. 2012) to determine the value of the constants in each model, using SPSS v. 25, in the nonlinear regression routine, which employs iterative estimation algorithms. The program continues iterating until the constant values are found. The models used were the following:

$L_t = L_{\infty}(1-e^{-K(t-to)})$ VB model

$L_t = L_{\infty}e^{-e-K(t-to)}$ Gompertz model

$L_t = L_{\infty}/(1+e^{-K(t-to)})$ logistic model

$MI = a + bL_i - cL_i'$ bent line model

where L_t: length at time or age class t; L_{max}: maximal length; K: growth rate; t_0: theoretical time when length is zero; MI: molt increment; L_i: average length of age class *i*; L_i': difference of L_i and the length preceding in the age class; and *a*, *b*, and *c* are constants. The results from each model, along with the standard errors and the residual sum of squares, were computed. The best-fit model was selected by Akaike's information criterion (AIC) (Burnham & Anderson 2002), using the negative logarithm of the maximum-likelihood method (Cerdenares-Ladrón de Guevara et al. 2011).

In contrast, the increment in mm $week^{-1}$ was obtained with the linear model proposed by Pérez-Castañeda et al. (2019):

$$BDI = a + b \times \text{temperature (°C)}$$

where BDI is body size increment in mm $week^{-1}$, *a* is the ordinate at the origin, and *b* is the slope:

$$BDI = -3.89 + 0.27 \times \text{temperature (°C)} \quad P < 0.05$$

Once the average lengths for each size class are obtained using the Bhattacharya model, the class frequencies are summed to obtain the number of individuals in each class, which decreases as individuals grow larger. Mortality is then calculated using Ricker's (1975) exponential model ($N_j = N_0 e^{-zt}$), which relates the number of juveniles in each age class (N_j) to the relative age class (t = 1, 2, 3…), N_0 is the initial theoretical number of shrimps, and Z is the mortality rate. Survival (S), expressed as a percentage, is given by: $S\% = 100(e^{-z})$.

RESULTS

Environmental factors

The highest concentration of dissolved oxygen was in October, at 6.23 ± 0.45 mg L^{-1}, while the lowest was in June, at 3.01 ± 1.31 mg L^{-1}. The highest average pH occurred in December at 8.17 ± 0.09, and the lowest in October at 7.08 ± 0.05. The temperatures recorded throughout the study period varied with the climatic seasons: the highest average temperature was 30.79 ± 1.51°C in June, while the lowest was 23.38 ± 0.05°C in February. The values of total dissolved solids were higher in August, with 87.43 ± 11.20 ppt, while the lowest values were found in October, with 12.39 ± 0.94 ppt. In June, the highest average salinity, 32.78 ± 1.43, was recorded; the lowest, 16.82 ± 1.42, was recorded in October (Table 1). Regarding the average values per sampling site, the lowest dissolved oxygen value was 3.92 ± 1.33 mg L^{-1}, recorded at site 2; the highest was 4.92 ± 1.03 mg L^{-1}, recorded at site 1. The highest pH value was 7.80 ± 0.39 at site 3, while the lowest was 7.48 ± 0.44 at site 2. The highest average temperature was 28.68 ± 3.89°C, recorded at site 4, while the lowest

Table 1. Environmental factors (EF) for months and sampling sites in Laguna Larga, part of the Mandinga Lagoon System, Veracruz. AVG: average, BB: Bahía Blanca, BM: Biosfera Manglares, DO: dissolved oxygen, EC: El Conchal, EF: environmental factor, PT: Punta Tiburon, S: site, Temp: temperature, SD: standard deviation, TDS: total dissolved solids Sal: salinity.

			Site			EF (AVG ± SD) by month
Month	EF	S1 (BB)	S2 (EC)	S3 (PT)	S4 (BM)	AVG ± SD
February	DO (mg L^{-1})	5.56	4.99	3.85	4.18	4.65 ± 0.78
	pH	8.1	8.07	8.05	8.04	8.07 ± 0.03
	Temp (°C)	23.31	23.38	23.42	23.41	23.38 ± 0.05
	TDS (ppt)	24.99	21.41	21.36	20.19	21.99 ± 2.08
	Sal	29.96	27.61	27.43	25.82	27.71 ± 1.71
April	DO (mg L^{-1})	4.5	3.64	3.79	4.03	3.99 ± 0.38
	pH	7.48	7.43	7.87	7.7	7.62 ± 0.20
	Temp (°C)	25.92	26.51	26.66	26.78	26.47 ± 0.38
	TDS (ppt)	21.53	22.4	22.63	22.56	22.28 ± 0.51
	Sal	31.14	32.54	32.91	32.79	32.35 ± 0.82
June	DO (mg L^{-1})	4.83	2.34	1.84	3.03	3.01 ± 1.31
	pH	7.26	7.31	7.83	8.03	7.61 ± 0.38
	Temp (°C)	29.41	29.58	31.95	32.24	30.79 ± 1.51
	TDS (ppt)	21.73	22.86	24.02	23.8	23.10 ± 1.04
	Sal	31.35	33.17	31.99	34.61	32.78 ± 1.43
August	DO (mg L^{-1})	3.75	2.99	3.34	3.43	3.38 ± 0.31
	pH	7.47	7.48	7.87	7.85	7.67 ± 0.22
	Temp (°C)	29.9	30.08	30.52	31.48	30.49 ± 0.71
	TDS (ppt)	72.13	85.97	95.87	95.73	87.43 ± 11.20
	Sal	9.33	11.26	12.68	12.64	11.48 ± 1.58
October	DO (mg L^{-1})	6.76	5.85	5.86	6.44	6.23 ± 0.45
	pH	7.03	7.04	7.12	7.11	7.08 ± 0.05
	Temp (°C)	28.21	28.98	29.15	29.51	28.96 ± 0.55
	TDS (ppt)	13.41	12.8	12.11	11.22	12.39 ± 0.94
	Sal	18.37	17.43	16.39	15.07	16.82 ± 1.42
December	DO (mg L^{-1})	4.74	4.77	5.09	4.7	4.83 ± 0.18
	pH	8.14	8.16	8.31	8.08	8.17 ± 0.09
	Temp (°C)	23.46	23.45	23.32	23.39	23.41 ± 0.06
	TDS (ppt)	24.91	24.35	22.82	21.17	23.31 ± 1.68
	Sal	31.19	31.83	29.6	27.24	29.97 ± 2.04
	DO (mg L^{-1})	4.92 ± 1.03	3.92 ± 1.33	3.98 ± 1.4	4.33 ± 1.19	
EF (AVG ± SD) by site	pH	7.48 ± 0.45	7.48 ± 0.44	7.80 ± 0.39	7.75 ± 0.37	
	Temp (°C)	27.38 ± 2.91	27.72 ± 3.03	28.32 ± 3.65	28.68 ± 3.89	
	TDS (ppt)	30.74 ± 21.17	33.68 ± 26.93	35.49 ± 31.04	34.89 ± 31.32	
	Sal	24.28 ± 9.28	25.25 ± 9.17	24.71 ± 8.54	24.47 ± 9.05	

value was 27.38 ± 2.91°C, recorded at site 1. The highest value of total dissolved solids was 35.49 ± 31.04 ppt at site 3, and the lowest value was 30.74 ± 21.17 ppt at site 1. The highest salinity value was 25.25 ± 9.17 at site 2, and the lowest value was 24.47 ± 9.05 at site 4 (Table 1).

The GLS model showed statistically significant differences across sampling months for the five measured parameters, whereas the site comparison revealed differences in dissolved oxygen, temperature, and pH (Table 2). Tukey's *post-hoc* test yielded statistically significant differences in dissolved oxygen concentrations between February and June and August, and between October and December and the remaining sampling months. The pH differed between February, October, and December and the remaining sampling months. Statistically significant temperature differences were also observed across all sampling months. In total dissolved solids, differences were found between August and the other sampling months. Salinity

Table 2. Generalized least squares analysis of the environmental factors among months and sampling sites in Laguna Larga belonging to the Mandinga System Lagoon, Veracruz. DO: dissolved oxygen, F: Fisher-Snedecor F test, *P*: probability, Sal: salinity, Temp: temperature, TDS: total dissolved solids.

	DO		Temp		TDS		Sal		pH	
Origen	F	*P*	F	*P*	F	*P*	F	*P*	F	*P*
Model	13.359	<0.001	81.818	<0.001	78.011	<0.001	73.983	<0.001	16.172	<0.001
Interception	1569.858	<0.001	50717.848	<0.001	989.335	<0.001	5675.215	<0.001	54079.672	<0.001
Month	18.587	<0.001	128.405	<0.001	124.509	<0.001	118.171	<0.001	23.194	<0.001
Site	4.645	0.017	4.174	0.025	0.514	0.679	0.335	0.8	4.468	0.02
Correlation (r)	0.94		0.99		0.99		0.99		0.95	

differed from the other sampling months ($P < 0.05$). Comparison of the data revealed statistically significant differences in dissolved oxygen between sites 1, 2, and 3; pH at sites 2 and 3; and temperature at sites 1 and 4 (Table 3).

According to the GLM analysis, brown shrimp abundance was related to temperature, salinity, and pH ($P < 0.05$). The superposition showed a value of less than one (0.29). On the other hand, according to the β values, pH followed by temperature had the greatest effect on changes in brown shrimp abundance (Table 4).

Abundance

A total of 1,741 brown shrimp juveniles were collected. August presented the highest number of juveniles with 771. The lowest abundance occurred in February, with 88 juveniles (Table 5). The data, after transformation with the natural logarithm, showed normal distribution ($P > 0.05$). ANOVA test of the abundances of juveniles revealed no statistically significant differences among sites ($F_{3,5} = 1.203$; $P = 0.355$) and among months ($F_{3,5} = 1.343$; $P = 0.297$).

Growth, mortality, and survival

The Bhattacharya method revealed five age classes. The analysis of the cohorts revealed no overlap (SI, values >2) (Table 6).

The ELEFANT I and progression analysis models yielded the initial parameters $K = 0.4$, $t_0 = 0.1$, and $L_{max} = 68$ mm. With these values, L_{max} ranged from 61.98 ± 1.89 mm with the logistic model to 78.65 ± 5.66 mm with the VB model. The growth rate ranged from 0.34 ± 0.05 with the VB model to 1.178 ± 0.11 with the logistic model. Bent line model presented values of A = 14.7 ± 3.57, B = 0.775 ± 0.04, and C = 2.12 ± 0.96. Of the four models applied, the bent line and Gompertz had higher fit percentages and lower AIC values for growth with weights (Table 7).

Using the linear model, which relates temperature to the growth rate, the average was 3.43 ± 0.9 mm week^{-1}, where the highest increment of 3.2 to 4.4 mm week^{-1} was obtained from April to October, with an average temperature of 29.19 ± 1.19°C, while a growth rate of 2.4 mm week^{-1} with an average temperature of 23.39 ± 0.02°C was obtained in December and February.

On the other hand, the relationship between the total length and weight was statistically significant ($P < 0.001$), with growth type allometric ($P < 0.05$) (Fig. 2).

The mortality rate for juveniles was Z = 1.987, corresponding to a 13.17% survival rate (Fig. 3). The negative exponential relationship between the age class and the number of juveniles was statistically significant ($P < 001$).

DISCUSSION

Environmental factors

Various authors have reported dissolved oxygen concentrations in the Mandinga Lagoon System. Reyes-Ascencio (2011) registered general concentrations of 8.57 mg L^{-1}, Vázquez-Botello et al. (2020) of 4 to 6 mg L^{-1}, and Camarena-Rosales (1982) from 3.7 mg L^{-1} in August to 7.3 mg L^{-1} in October. Likewise, Salcedo-Garduño et al. (2019) recorded concentrations ranging from 6.7 ± 0.5 mg L^{-1} in April to 9.3 ± 1.7 mg L^{-1} in November, and Rodríguez-Varela et al. (2025) reported concentrations between 6.67 and 10.95 mg L^{-1}. These values are consistent with the dissolved oxygen values found in this study, ranging from 3.01 ± 1.31 mg L^{-1} in the dry season to 6.23 ± 0.45 mg L^{-1} in the cold front season. According to the Environmental Protection Agency (2025), the increase in dissolved oxygen during a cold front is caused by both decreased water temperature, which increases the water's capacity to hold oxygen, and increased wind action, which enhances the mixing of oxygen from the atmosphere

Table 3. Comparison with Tukey's *post-hoc* test. DO: dissolved oxygen, P: probability, TDS: total dissolved solids, Sal: salinity, Temp: temperature.

		Environmental factor				
Comparison		DO (P)	TDS (P)	Sal (P)	pH (P)	Temp (P)
Feb	Apr			0.012	0.015	<0.001
Feb	Jun	0.007		0.006	0.012	<0.001
Feb	Aug	0.043	<0.001	<0.001	0.033	<0.001
Feb	Oct	0.009		<0.001	<0.001	<0.001
Feb	Dec					
Apr	Jun					<0.001
Apr	Aug		<0.001	<0.001		<0.001
Apr	Oct	<0.001		<0.001	0.003	<0.001
Apr	Dec				0.003	<0.001
Jun	Aug		<0.001	<0.001		
Jun	Oct	<0.001		<0.001	0.004	0.006
Jun	Dec	0.003			0.002	<0.001
Aug	Oct	<0.001	<0.001	0.004	0.001	0.023
Aug	Dec	0.017	<0.001	<0.001	0.006	<0.001
Oct	Dec	0.022		<0.001	<0.001	<0.001
Site 1	Site 2	0.041				
Site 1	Site 3	0.018				
Site 1	Site 4					0.027
Site 2	Site 3				0.01	

Table 4. Generalized linear model multinomial distribution for the abundances with respect to the environmental factors of months and sampling sites. B: indicates the direction (positive or negative) and magnitude of the relationship between the independent variable and the dependent variable. DO: dissolved oxygen, *P*: probability, Sal: salinity, TDS: total dissolved solids, Temp: temperature.

Hypothesis testing			
Origin	B	Wald's chi-square	*P*
DO (mg L^{-1})	-1.928	0.919	0.338
pH	-31.880	5.212	0.022
Temp (°C)	-15.558	5.050	0.025
TDS (ppt)	1.287	0.471	0.493
Sal	2.968	4.117	0.042

Table 5. Abundance (ind 10 m^{-2}) of *Penaeus* (*Farfantepenaeus*) *aztecus* juvenile collected in Laguna Larga estuary belonging to Mandinga System Lagoon, Veracruz, SW Gulf of Mexico. BB: Bahía Blanca, EC: El Conchal, PT: Punta Tiburón, BM: Biosfera Manglares.

	Site				
Month	S1(BB)	S2(EC)	S3(PT)	S4(BM)	Total
February	40	9	11	28	88
April	55	46	60	85	246
June	39	30	36	2	107
August	633	90	19	29	771
October	9	5	4	264	282
December	166	22	11	48	247
Total	942	202	141	456	1741

into the water. The recommended dissolved oxygen levels in water for optimal shrimp development and growth should be 4-10 mg L^{-1} (Lee & Wickings 1992, Clifford 1994, SENASICA 2003).

The pH in this study was neutral to slightly alkaline, similar to that found by Reyes-Ascencio (2011) and Solorzano et al. (2024) within the values established by the official Mexican standard (NOM-127-SSA1-1994). pH changes in estuarine systems are determined by the amount of organic matter transported or generated in the system (de la Lanza-Espino 2017). It is evident in the Estuary of Laguna Larga, where pH values buffer the water, preventing acidification (Bates 1973). Boyd (2001) notes that pH can affect shrimp metabolism. At pH 4 to 6, the shrimp show slow growth, whereas at pH 6 to 9, they show good growth.

In this region of the Gulf of Mexico, the temperature reported in the cold front season is between 23 and 24°C (Jasso-Montoya 2012, Avendaño-Álvarez 2013, Contreras-Espinoza 2016, Castañeda-Chávez et al. 2020), while Contreras-Espinoza (2016), Cházaro-Olvera et al. (2024), and Rodríguez-Varela et al. (2025) registered temperatures of 29 to 30°C in the dry and

Table 6. Average length (mm) of each age class *Penaeus* (*Farfantepenaeus*) *aztecus* juvenile. a) Average of each age class, b) comparison with the separation index (SI) of Sparre & Venema (1997).

a	Age relative	Average length (mm)
	1	11.65
	2	29.65
	3	44.65
	4	55.15
	5	60.5
b	Comparison	SI
	L1 to L2	3.23
	L2 to L3	3.17
	L3 to L4	2.99
	L4 to L5	2.01

rainy seasons. These results are consistent with the values obtained in this study. Thus, the changes in the estuary's temperature in Laguna Larga respond to the region's climatic seasons (Zavala-Hidalgo et al. 2006, Salas-Monreal et al. 2020). Optimal growth of brown shrimp is reported to occur at temperatures between 22.5 and 30°C (Zein-Eldin & Griffith 1969). On the other hand, the temperatures recorded in this work did not exceed the maximum permissible limit of 35°C defined by the official Mexican standard, which applies to discharges into rivers, natural and artificial reservoirs, and other designated receiving bodies. Compliance ensures that the thermal energy from the discharge does not disrupt the biological balance of the environment (NOM-001-SEMARNAT-2021).

In the estuary of Laguna Larga, total dissolved solids in months and sites exceeded the maximum permissible limit of 1,000 ppm established by the official Mexican standard NOM-001-SEMARNAT-2021 and NOM-127-SSA1-1994 for drinking water. In the region, Cházaro-Olvera et al. (2023, 2024) found high values of total dissolved solids. These concentrations of dissolved solids are due to the transport of the Jamapa River into the Boca del Río zone (Aragón-López et al. 2017) and to the effects of water entering the estuaries during high tide, which is reflected in a similar behavior of salinity (Turner & Millward 2002).

Rodríguez-Varela et al. (2025) reported salinity values in the Mandinga System Lagoon ranging from 14.85 to 31.48, while those recorded in the estuary of Laguna Larga ranged from 5.2 in the rainy season to 29.93 in the dry season (Camarena-Rosales 1982, Reyes-Ascencio 2011, Solorzano et al. 2024). In the present work, salinity ranged from 11 to 34. Using the Venice System for the Classification of Marine Waters According to Salinity (1958), the estuary of Laguna Larga can be considered mixoeuhaline during dry times, mixomesohaline during rainfall, and mixopolihaline in cold fronts. Optimal growth of brown shrimp occurs at a salinity of 15 (Zein-Eldin & Griffith 1969). Therefore, the salinity recorded in this work is adequate for the growth and development of juvenile brown shrimp.

According to the GLM analysis, during the sampling months, the physicochemical parameters recorded and the species abundances are related, as reported by Sanvicente-Añorve et al. (2010) for seven coastal lagoons in the Gulf of Mexico.

Abundance

August, which corresponds to the rainy season, recorded the highest abundance of brown shrimp juveniles. In this regard, Cházaro-Olvera et al. (2020) also found the highest mysis abundance in brown shrimp in the southern area of the Veracruz Reef System during the rainy season, an area adjacent to the estuary entrance of Laguna Larga. On the other hand, Cervantes-Hernández et al. (2008) reported that Mexican shrimp populations exhibit high reproductive activity during rainy and cold-front seasons. Brown shrimp spawn on the continental shelf of the Gulf of Mexico year-round (Gallaway & Reitsema 1981). After hatching, planktonic larvae and postlarvae gradually move inshore, driven by westerly winds. Postlarvae are recruited to estuaries during winter and spring, peaking in late February and March (Li & Clarke 2005), which explains why the present study found a different abundance of brown shrimp juveniles of 44.3 mm in August.

Growth

In February, which corresponds to the season of cold fronts, the smallest juveniles of shrimp showed a low growth rate of only 2.4 mm per week, related to the lowest temperature values (Pérez-Castañeda et al. 2019). From April to October, the estimated growth rate was high, ranging from 4 to 4.7 mm per week, related to the higher temperatures. The growth rates evaluated with the model of Pérez-Castañeda et al. (2019) were consistent with those obtained in this work and correspond temporally to 8.6 weeks, yielding growth rates of 3.5 and 5.5 mm week^{-1} for the VB and Gompertz models, respectively. So, the higher the water temperature, the higher the growth rates. In this regard, the relationship between temperature and shrimp growth rates has been reported in both field and

Table 7. Growth models of Von Bertalanffy (VB), Gompertz, logistic, and bent-line applied to juveniles of *Penaeus* (*Farfantepenaeus*) *aztecus* collected in the estuary Laguna Larga, belonging to the Mandinga System Lagoon, Veracruz, SW Gulf of Mexico, and test of fit with the weight of Akaike information criterion method. A, B, C, constants of the Bent-Line model; BSI: body size increase; K: growth rate; Lmax: maximal length; RSS: residual sum of squares; Temp: temperature; t_0: hypothetical age or time when length was equal to zero.

Model		Total sample
VB	Lmax	78.65 ± 5.66
	K	0.34 ± 0.05
	t_0	0.54 ± 0.07
	RSS	2.51
Gompertz	Lmax	65.79 ± 0.71
	K	0.75 ± 0.02
	t_0	1.72 ± 0.02
	RSS	0.261
Logistic	Lmax	61.98 ± 1.89
	K	1.18 ± 0.11
	t_0	2.149 ± 0.09
	RSS	4.17
Bent line	A	14.7 ± 3.57
	B	0.775 ± 0.04
	C	2.12 ± 0.96
	RSS	0.17

Growth model	AIC	AIC diff	Weight
Bent-Line	-35.41	0	70.3048
Gompertz	-33.69	1.72	29.6934
VB	-14.03	21.38	0.0016
Logistic	-9.62	25.79	0.0002

Month	Feb	Apr	Jun	Aug	Oct	Dec
BSI (mm $week^{-1}$)	2.4	3.2	4.4	4.3	3.9	2.4
Temp (°C)	23.38	26.47	30.79	30.49	28.96	23.41

laboratory studies (Zein-Eldin & Griffith 1969, Staples & Heales 1991, O'Brien 1994, Pérez-Castañeda & Defeo 2005). Therefore, as temperature increases, shrimp will present shorter intermolt periods (Staples & Heales 1991). While the change from one age class to another is faster, the increase in size may be smaller at lower temperatures.

Pérez-Castañeda et al. (2019) observed the highest growth rate of brown shrimp at the lowest salinity in Laguna Madre. It corresponded to the period of highest water temperature in the lagoon, consistent with the results of this work. In conclusion, the growth of brown shrimp is more strongly influenced by temperature than by salinity (Zein-Eldin & Griffith 1969).

Positive allometry was observed, indicating that weight increases faster than length. The shrimp is becoming "fatter" or more robust as it grows, which is often observed in juveniles or under ideal environmental conditions (Kaka et al. 2019).

Mortality and survival

A high mortality rate and a high growth rate were obtained; from this, it can be established that there is a relationship between growth and survival, thus evidencing the cost-benefit relationship, a mechanism present in populations for the distribution of resources (Begon et al. 1998).

Considering the highest abundance in August and the decrease until February, a total mortality rate of 0.31 was calculated. This rate is consistent with those reported by other authors, who obtained total monthly mortality rates for brown shrimp ranging from 0.19 to 0.34 (Klima 1989, Arreguín-Sánchez et al. 1997, Gracia 1997, Deval & Denis 2025).

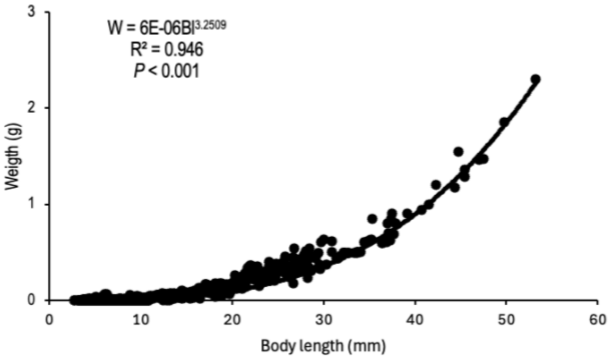

Figure 2. Weight-length relation of brown shrimp juveniles in Laguna Larga belonging to the Mandinga System Lagoon, Veracruz, Mexico. W: weigth (g), Bl: body length (mm).

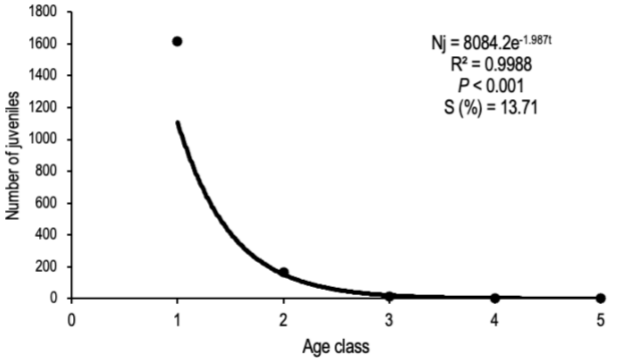

Figure 3. Mortality and survival of brown shrimp juveniles in Laguna Larga belonging to the Mandinga System Lagoon, Veracruz, Mexico. Nj: number of juveniles, t: time (age class).

Regarding survival, Deval & Deniz (2025) found rates ranging from 36.8 to 58.5% in populations subject to fishing; in the present work, for juveniles in the estuary of Laguna Larga, survival rates were lower, ranging from 20.16 to 35.04%.

The highest concentrations of total dissolved solids, such as those that occurred in August in this study, can negatively affect crustacean respiration by reducing dissolved oxygen levels in the water. The values were also low in August, with increasing salinity, which stresses the crustaceans. High total dissolved solids, particularly from salts, require increased energy for osmoregulation, which can raise respiration rates and negatively impact growth and overall survival (Lucu & Ziegler 2017).

In conclusion, the dissolved oxygen in the water of Laguna Larga, part of the Mandinga Lagoon System, is consistent with values reported by other authors and holds for pH values that are adequate for the growth and development of brown shrimp. Changes in temperature in the estuary of Laguna Larga correspond to the region's climatic seasons, and changes from one age class to another are faster. However, the increase in size is smaller at lower temperatures. The total dissolved solids at months and sites exceeded the maximum permissible limit, decreasing dissolved oxygen in the water and affecting metabolism. In dry periods, Laguna Larga can be considered mixoeuhaline; in rainy periods, mixomesohaline; and during cold fronts, mixopolihaline, with adequate salinity for the development of brown shrimp. August, which corresponds to the rainy season, registered the highest abundance of juveniles of brown shrimp, corresponding to one of the peaks of reproduction of brown shrimp in the Gulf of Mexico. From April to October, the estimated growth rate ranged from 4 to 4.7 mm per week.

The growth rates of brown shrimp showed a close relationship with water temperatures, with higher growth rates at higher temperatures.

On the other hand, positive allometric growth occurred in April, June, October, and December, reflecting the distribution of energy resources to growth in body biomass. June and August had the highest mortality rates and the lowest survival, which was the last establishment of a relationship trade-off with growth: during these months, a high rate of increase in size was observed. Survival rates in the estuary of Laguna Larga were lower, ranging from 20.16 to 35.04%. The results allow us to understand the population dynamics of the brown shrimp at the juvenile stage in Laguna Larga, Mandinga, Veracruz.

Credit author contribution

S. Cházaro-Olvera: conceptualization, validation, methodology, formal analysis, writing-original draft and funding; A. Citlali Morales-Olguin: methodology, formal analysis and data curation; Á. Morán-Silva, methodology, review and editing; J. Montoya-Mendoza: methodology, validation, supervision, review and editing; R. Chávez-López: methodology, data curation, formal analysis, review and editing; J. Montoya-Benítez: methodology, review and editing. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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