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Scientific Article

Ecomorphology of yellowtail lambari (Characiformes: Characidae) in the neotropical semi-arid region, Brazil

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ABSTRACT

The ecomorphological patterns of the *Astyanax lacustris* in different environments (lotic and lentic) of the semi-arid region of Pernambuco were analyzed using 25 linear morphometric measurements on 240 specimens (120 males and 120 females), with standard lengths ranging from 24.25 to 91.50 mm. These data were converted into 16 ecomorphological attributes and correlated with environmental characteristics. The principal component analysis (PCA) explained 81.64% (first and second components) of the data variation, highlighting sexual dimorphism in specimen size and noticeable variation among individuals of the same sex in different environments. Specimens from lotic environments showed higher caudal peduncle compression index (CPCI) values, while the pectoral fin aspect ration (PFAR) was more pronounced in lentic environments. Overall, females exhibited a wide morphometric variation. Analysis of linear morphometry in different water bodies indicated an intrinsic variation related to hydrodynamics linked to sexual dimorphism and water flow speed. Further studies are suggested to investigate whether factors such as macrophytes and different levels of water depth and flow contribute to this morphometric variation of species in the semi-arid region.

Keywords: Caatinga; Habitat diversity; São Francisco river basin; *Astyanax*.

Ecomorfologia do lambari-do-rabo-amarelo (Characiformes: Characidae) no semiárido neotropical, Brasil

RESUMO

Os padrões ecomorfológicos da espécie Astyanax lacustris em diversos ambientes (lótico e lênticos) da região semiárida de Pernambuco foram analisados usando 25 medidas morfométricas lineares em 240 espécimes (120 machos e 120 fêmeas), com comprimentos padrão variando de 24,25 a 91,50 mm. Esses dados foram convertidos em 16 atributos ecomorfológicos e correlacionados com características ambientais. A análise de componentes principais (PCA) revelou que 81,64% (primeiro e segundo componente) da variação dos dados foi explicada, destacando o dimorfismo sexual no tamanho dos espécimes e uma notável variação entre indivíduos do mesmo sexo em diferentes ambientes. Os espécimes de ambientes lóticos mostraram maiores valores de índice de compressão do pedúnculo caudal (ICPC), enquanto a razão do aspecto da nadadeira peitoral (RANP) foi mais pronunciado em ambientes lênticos. Em geral, as fêmeas exibiram uma ampla variação morfométrica. A análise da morfometria linear em diferentes corpos d'água indicou uma variação intrínseca relacionada à hidrodinâmica, ligada ao dimorfismo sexual e à velocidade do fluxo de água. Sugere-se que estudos adicionais sejam realizados para investigar se fatores como macrófitas e diferentes níveis de profundidade e fluxo de água contribuem para essa variação morfométrica das espécies na região semiárida.

Palavras-chave: Caatinga; Diversidade de hábitat; Bacia do Rio São Francisco; *Astyanax*.

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INTRODUCTION

Ecomorphology studies the relationship between morphology and ecology of individuals, populations, and communities, analyzing its evolutionary consequences (Gatz, 1979; Winemiller, 1991). Different researchers have used this tool to understand and relate morphological variations and different types of habitats with the biological aspects of the studied species (Bano and Serajuddin, 2021; Soria-Barreto et al., 2019; Souza and Pompeu, 2020). The morphology of organisms and their habitats are entirely correlated, that is, the phenotype of the organism is associated with the characteristics of the environment and indirectly with the available resources, due to environmental and ecological pressures for survival (Gatz, 1979; Howe et al., 2022; Manna et al., 2020; Paz Cardozo et al., 2021).

In recent years, studies have been conducted in neotropical rivers and streams aiming to describe the ecomorphological patterns of fish assemblages to understand the niche characteristics of each species. However, knowledge about small fish in these environments is still a challenge, being the least studied (Araújo et al., 2012). Among the small-sized species, the genus *Astyanax* Baird & Girard (1854), belonging to the family Characidae, order Characiformes, is one of the most diverse, with about 128 valid species (Toledo-Piza et al., 2024) and an increase of about 40 new species in the last ten years (Salgado, 2021). This genus is composed of fish with a remarkable ability to adapt to different environmental conditions and a wide distribution from the south of the United States of America to the north of Argentina (Garita-Alvarado and Ornelas-García, 2021; Pasa et al., 2019).

Brazil contributes almost 50% of the valid species of the genus (Fricke et al., 2022), being exclusively freshwater and with few morphological, ecological, and behavioral differences among them. They range from still-water environments to large rivers with areas of current. The species *Astyanax lacustris* (Lütken, 1875) is native to the São Francisco River basin, but its distribution is extended to other basins (de Melo et al., 2016; Lucena and Soares, 2016). The species presents apparent sexual dimorphism, with females being and more significant than males and presenting a more rounded body (Stevanato; Ostrensky, 2018).

Studies related to the ecomorphology of species of the genus *Astyanax* have been conducted, highlighting the work with the species: *Astyanax bifasciatus*, *Astyanax minor*, *Astyanax intermedius*, *Astyanax rivularis*, and *Astyanax altiparanae* in the southeast and central-west regions (Mise et al., 2013; Oliveira et al., 2010; Souza et al., 2014). However, studies directed at the species *A. lacustris* focused on this science are still scarce and can provide relevant information about its life strategy and interactions with other organisms in the ecosystem.

Thus, we aimed to analyze the ecomorphological patterns of the species *A. lacustris* by comparing lotic and lentic water bodies in the semi-arid region of the state of Pernambuco, Brazil, correlating its morphology to environmental characteristics.

MATERIALS AND METHODS

Study area

The study was carried out in different water bodies in the semi-arid neotropical region located in the state of Pernambuco, all characterized by personal observations: Pajeú River, downstream of Serrinha Dam (08.2090ºS, 038.5332ºW), Brígida River, downstream Chapéu Dam (07.9945ºS, 039.5659ºW), both characterized with continuous and turbulent water flow (lotic environment), Cachoeira I Dam (07.9368ºS, 038.3306ºW), Jazigo Dam (07.9421ºS, 038.1513ºW), Jureminha Dam - São José de Egito (07.4677ºS, 037.2894ºW) and João Barbosa Lake - Triunfo (07.8363ºS, 038.1049ºW), both characterized with low water flow, the last four sites being considered as lentic environments (Fig. 1).

The points downstream of the Serrinha and Chapéu dams present continuous water flow throughout the year, with current velocity higher than 5 m/s; the stretches of the Cachoeira I and Jazigo weir present intermittent flow

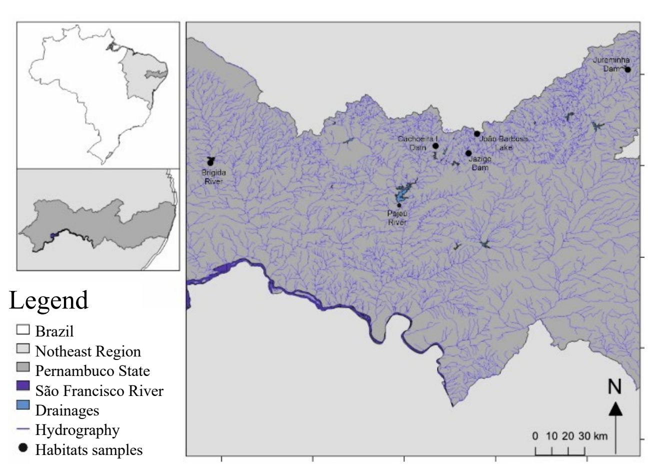


Figure 1. Geographic location of the collection areas of the species *Astyanax lacustris*, in water bodies of the São Francisco River basin, Pernambuco, Brazil.

throughout the year, in function of the precipitation level of the region (Diniz et al., 2021; Nascimento Filho et al., 2019), high density of floating and submerged macrophytes; João Barbosa Lake has a small stream supply, average depth above 12 m and no macrophytes; and Jureminha weir has low depth and plenty of submerged macrophytes.

Sampling

Sampling was carried out in March 2020, using cast nets (2.5 m; 20 mm mesh), hand nets (40 cm; 5 mm mesh) and trawl net (10 × 2.5; 5 mm mesh), in accordance with the authorization of Biodiversity Authorization and Information System nº 24709-3 and the Ethics Committee on Animal Use of Universidade Federal Rural de Pernambuco (License nº 023/2019). In each location, 40 specimens were captured, 20 males and 20 females, thus avoiding sexual variations in body shape (Cano et al., 2020; Oliveira et al., 2010; Prado et al., 2016). Subsequently, the specimens were placed in a lethal solution of eugenol (Lucena et al., 2013), then fixed in 4% formalin solution and transported to the Laboratory of Ecology and Systematics of Fishes, of the Universidade Federal Rural de Pernambuco, Academic Unit of Serra Talhada.

Calculation and analysis of the ecomorphological attributes

Twenty-five morphometric measurements were performed, listed in Table 1. All measurements were taken with the aid of a 0.01-mm precision digital pachymeter, related to the trunk, fins, head, and mouth, according to the studies of Cano et al. (2020), Gatz (1979), and Oliveira et al. (2010), and were chosen because they were related to habitat use. From the set of linear measurements, 16 ecomorphological attributes related to the environment were calculated and can be visualized in Table 2.

To summarize the morphological variations, the measurements were submitted to principal component analysis applied to the correlation matrix, considering this the ecomorphological indices to identify the existence of different morphological patterns and the characterization between the different populations simultaneously (Baldasso et al., 2019). To discriminate, classify, and group possible ecomorphological groups of *A. lacustris* populations, a discriminant function analysis (DFA) was performed ($p < 0.01$) with a coefficient stabilized by the Jackknifed method of resampling.

To compare the total length of specimens between sexes and between different environments, the Mann-Whitney's test (Wilcoxon rank-sum test) was used ($p < 0.05$). The descriptive statistics are represented by a box plot, in which the central horizontal bar represents the median; the lower and upper boxes represent the first and third quartiles, respectively; and the extreme bars represent the minimum (lower) and maximum (upper) values.

Subsequently, a multivariate normality test was performed to verify that the probability distribution associated with the data set has a normal distribution, followed by a multivariate analysis of variance and Dunn's post-hoc test for paired comparisons

Table 1. Morphometric measurements used to obtain the ecomorphological attributes in *Astyanax lacustris* in the semi-arid neotropical region.

Item	Measurement	Description	Item	Measurement	Description
1	TL	Total length	14	CPL	Caudal peduncle length
2	SL	Standard length	15	CPW	Caudal peduncle width
3	CFL	Caudal fin length	16	MBH	Maximum body height
4	CFH	Caudal fin height	17	MBW	Maximum body width
5	HL	Head lenght	18	PFW	Pectoral fin width
6	HW	Head width	19	PFL	Pectoral fin length
7	HH	Head height	20	PFW	Pelvic fin width
8	ED	Eye diameter	21	PFL	Pelvic fin length
9	EH	Eye height	22	DFH	Dorsal fin heigth
10	MMH	Maximal mouth height	23	DFL	Dorsal fin length
11	MWM	Maximal width of mount	24	AFH	Anal fin height
12	HBM	Height of body midline	25	AFL	Anal Fin length
13	CPH	Caudal peduncle height			

Table 2. Ecomorphological attributes in *Astyanax lacustris* in the semi-arid neotropical region.

Item	Measurement	Description	Item	Measurement	Description
1	CI	Compression index	9	RMH	Relative mouth height
2	RBH	Relative body height	10	REP	Relative eye position
3	RCPL	Relative caudal peduncle length	11	RHW	Relative head widht
4	CPCI	Caudal peduncle compression index	12	RHH	Relative head height
5	VFI	Vental flattening index	13	RWCP	Relative width of caudal peduncle
6	PFAR	Pectoral fin aspect ratio	14	RHCP	Relative height of caudal peduncle
7	RHL	Relative head length	15	RCFL	Relative caudal fin length
8	RWM	Relative width of mouth	16	RHCF	Relative height of caudal fin

between populations ($p < 0.01$). All analyses were performed in PAST version 4.03 software (Hammer et al., 2001).

RESULTS

A total of 240 specimens were analyzed, with standard lengths ranging from 24.25 to 91.5 mm, with mean and standard deviation of 63.74 ± 12.58 mm. Females had lengths ranging from 45.44 to 91.50 mm (71.25 ± 9.07 mm) and males from 24.25 to 76.15 mm (56.24 ± 11.04 mm). The lotic environment (Serrinha and Brígida) has individuals with standard lengths between 24.25 and 91.32 mm (62.73 ± 15.19). The lentic environment (João Barbosa Lake, Cachoeira I Dam, Jazigo Dam, and Jureminha Dam) had size ranges between 38.75 and 91.50 mm (64.32 ± 11.08 mm).

Mann-Whitney's test showed a significant difference between the size of specimens (total length) of different sexes (MW1:240 = 9.4715, $p < 0.001$), indicating that there was sexual dimorphism. No difference was observed between the mean size of the specimens in the different environments (MW1:240 = 0.6873, $p = 0.4919$), indicating that the variation found in the other analyses will be related to the different localities, and not to ontogeny.

A principal component (PC) analysis was performed, whose correlation matrix showed that the first two axes were significant, accounting for 81.64% of the variance, with the first axis (PC1) representing 51.34% influenced by the pectoral fin aspect ratio (PFAR) ecomorphological index, and the second axis (PC2) representing for 30.30% influenced by the compression index (CI) and caudal peduncle compression index (CPCI) indices (Fig. 2).

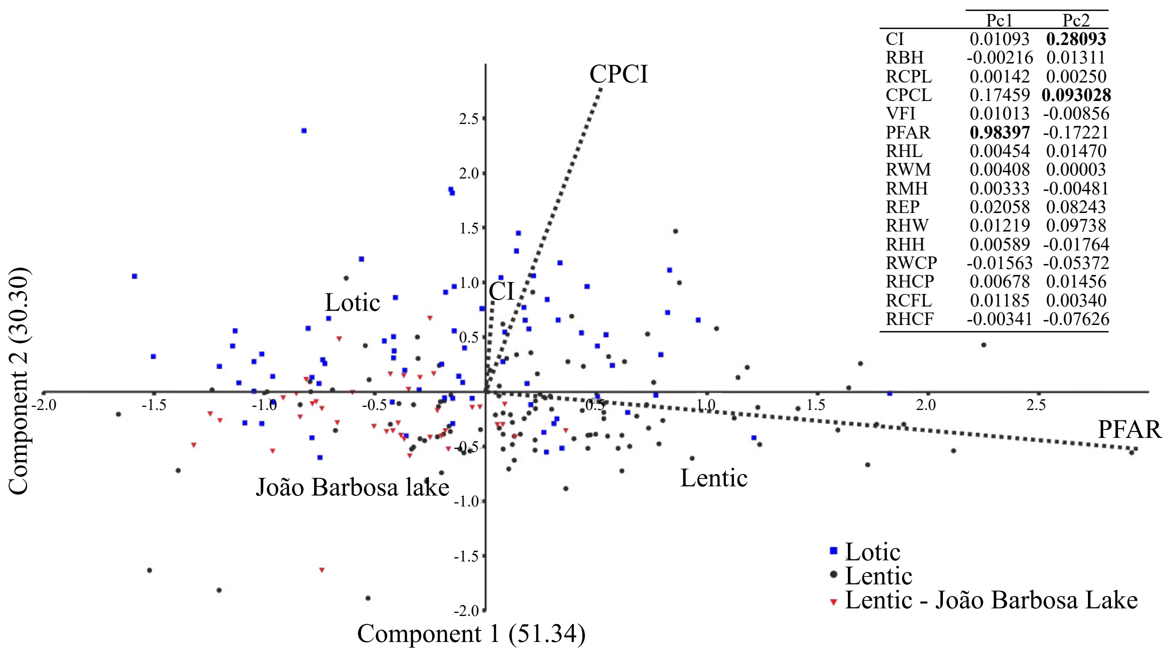
Discriminant function analysis showed a significant difference in ecomorphological attributes (Wilk's $\lambda = 0.239$, F10.466 = 48.59, $p < 0.01$). The main attributes were CPCI, CI, and PFAR. These factors contributed to the segregation in axis 1 of Serrinha and Brígida (lotic environment) from the other sites, while axis 2 showed a noticeable segregation of João Barbosa Lake (lentic environment, characterized by not having shallow areas and macrophytes) from the other sites (Fig. 3).

When analyzing the correct allocation of the groups, through DFA and the verification of the confusion matrix through the Jackknifed method, it was observed with accuracy of 65.42% that Jazigo Dam had a higher incorrect allocation (25%), followed by Brígida (12.5%) and Cachoeira I Dam (2.5%), where these specimens were allocated to the other points making the environments João Barbosa Lake, Jureminha Dam and Serrinha Dam have an increase of 22.5, 10.0 and 7.5% respectively.

Populations from environments with higher current velocity and continuous water flow (lotic) showed higher values of CPCI, while a great value in PFAR was attributed to the lentic environments (Fig. 4). The attribute IC only showed a significant difference (KW-H5:240 = 47.31, $p < 0.01$) among female specimens for the lotic environment, which resulted in a separation of this environment from the others, with the other attributes not showing significant differences.

DISCUSSION

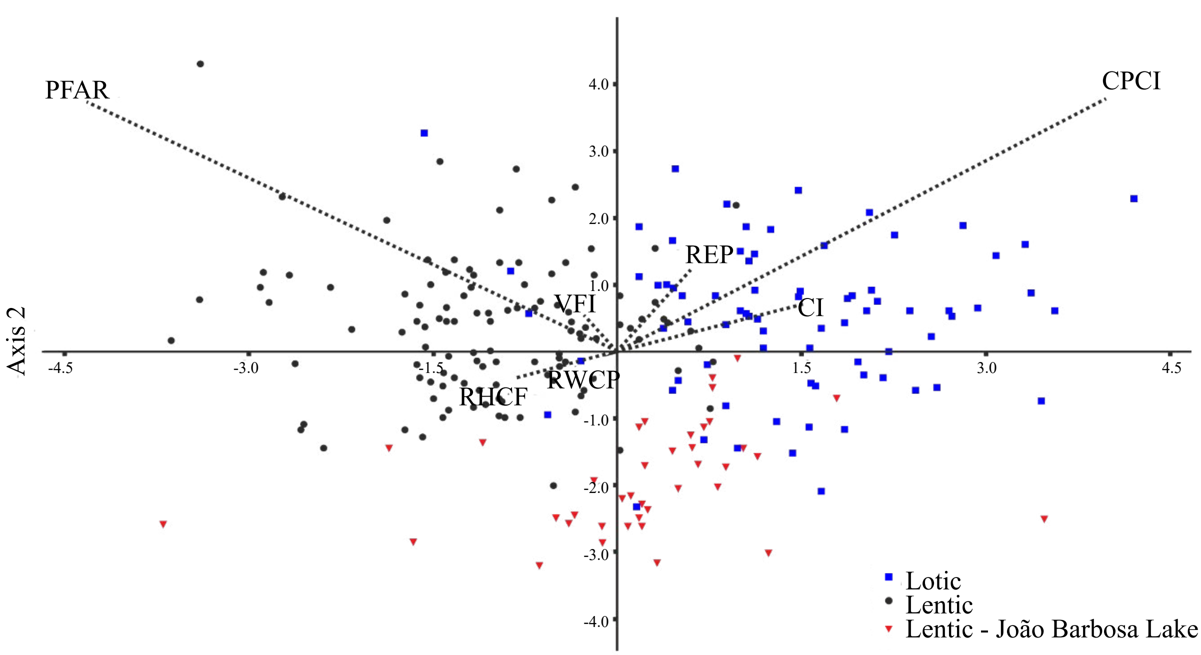
In our study, specimens from different localities with distinct environmental characteristics were analyzed, identifying population differences. The difference in size structure between sexes was also observed for other species of the genus in other localities, indicating that females are larger than males (Cordeiro et al., 2019; Pinheiro et al., 2019; Silveira et. al., 2020). Organisms from different habitats are exposed to wide variations in environmental conditions, causing these individuals to display diverse phenotypes as they are exposed to these conditions (Perazzo et al., 2019). The semiarid region



	Pc1	Pc2
CI	0.01093	**0.28093**
RBH	-0.00216	0.01311
RCPL	0.00142	0.00250
CPCL	0.17459	**0.093028**
VFI	0.01013	-0.00856
PFAR	**0.98397**	-0.17221
RHL	0.00454	0.01470
RWM	0.00408	0.00003
RMH	0.00333	-0.00481
REP	0.02058	0.08243
RHW	0.01219	0.09738
RHH	0.00589	-0.01764
RWCP	-0.01563	-0.05372
RHCP	0.00678	0.01456
RCFL	0.01185	0.00340
RHCF	-0.00341	-0.07626

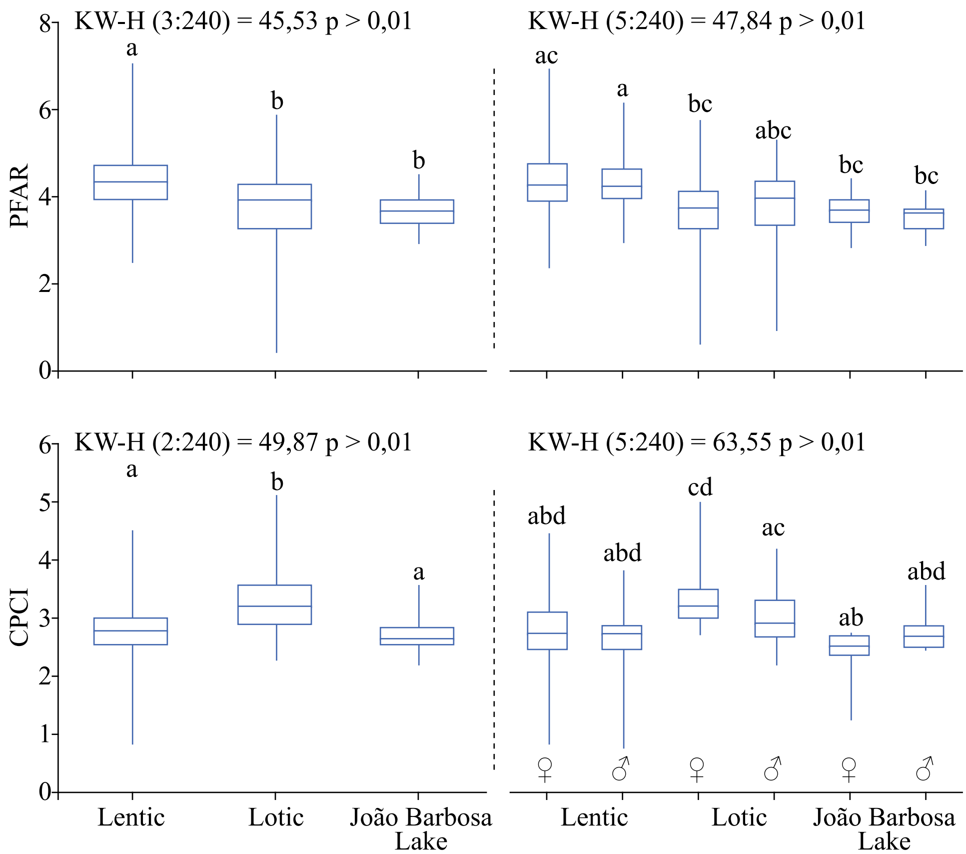
PFAR: pectoral fin aspect ratio; CPCI: caudal peduncle compression index; CI: compression index.

Figure 2. Distribution of *Astyanax lacustris* scores in the first two axes of the principal component analysis applied to the 16 ecomorphological indices. Values of the scores in the table in the upper right corner.



PFAR: pectoral fin aspect ratio; REP: relative eye position; VFI: vental flattening index; RWCP: relative height of caudal peduncle; RHCF: relative height of caudal fin; CI: compression index.

Figure 3. Distribution of *Astyanax lacustris* scores in the first two axes of the discriminant function analysis applied to the 16 indices.



PFAR: pectoral fin aspect ratio; CPCI: caudal peduncle compression index.

Figure 4. Values of means, standard deviations, and minimum and maximum values for significant ecomorphological attributes of *Astyanax lacustris*. On the right, values are presented by the environment, and on the left, values are presented by sex. The letters represent significant differences.

presents a hydrographic network with different types of natural and artificial water bodies with distinct characteristics, forming a range of systems and habitats exposed to different environmental conditions and hydrological disturbances (Barbosa et al., 2012). Populations in semiarid neotropical regions exhibit special properties that are directly dependent on environmental characteristics, leading to the ability of some populations to explore more complex habitats than others.

Species inhabiting lotic environments often exhibit a fusiform body shape which allows for better constant swimming and reduced drag due to high current flow, while species from lentic environments generally have lower anterior regions and larger caudal peduncle areas, facilitating faster burst velocity and maneuverability (Perazzo et al., 2019). The specimens analyzed showed these characteristics, but females from the lotic and deep lake environments showed significant differences ($p < 0.001$) with respect to body height compared to individuals of both sexes from the lentic environment, showing higher values.

Intraspecific differences in body height are often observed in organisms from environments with continuous water flow (Breda et al., 2005). However, this pattern was not observed in this study, which may be related to a better adaptation of the species to the environment, consequently, in changes in the hydrological level and current velocity, because it is in the semi-arid region, which suffers from large fluctuations in rainfall. This region presents a constant change of dry and wet zones, due to the irregularity of rainfall and high rates of evaporation, resulting in high variation of its annual flows (Bezerra et al., 2021; Soares et al., 2021).

The ecomorphological analysis attempts to link the anatomy of living organisms with different ecosystems to link morphology with ecology and ensure that the morphological evolution of an organism predicts a specific environmental characteristic, such as food resource or habitat use. Regarding the ecomorphological attributes analyzed, it was possible to find consistent patterns in the relationship between morphological and habitat traits of the species *A. lacustris*, confirming the structural differences related mainly to CPCI and PFAR relating with water flow speed and maneuverability, which may mean difference in its hydrodynamics (Oliveira et al., 2010; Prado et al., 2016).

Functional traits associated with fish swimming are generally correlated with ecological gradients, which will vary depending on habitat complexity, water flow, and predator pressure, and may thus present two primary swimming modes, constant and unstable, along this ecological gradient (Costa-Pereira et al., 2016). The fins have functions related mainly to aquatic locomotion, either as the main propulsive organ, being the caudal fin primordial for producing impulses for continuous and discontinuous locomotion, and the pectoral fin important in braking and yawing (Breda et al., 2005; Gatz, 1979; Watson and Balon, 1984).

CONCLUSIONS

The present study on the linear morphometric of *A. lacustris* from different water bodies in the semi-arid region of the Pernambuco state allowed us to conclude that ecomorphological attributes are shown to be related to environmental aspects. There was an intrinsic morphometric variation of the species when related to the hydrodynamics of different sites. There were both intrapopulation sexual dimorphism and notorious variation also between the same sex from different environments. Populations from environments with higher current velocity and continuous water flow (lotic) showed higher values of CPCI, and PFAR was attributed to the lentic environments. In general, females presented a greater range of variation.

Considering the aspects observed in the present research, it is further suggested more studies to elucidate whether factors such as the presence of macrophytes and environments with different levels of depth and different constant water flows can influence this morphometric variation of the species in the semi-arid region.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILITY STATEMENT

All dataset were generated and analyzed in the current study.

AUTHORS' CONTRIBUTION

Conceptualization: França EJ, Mendes RAS; **Investigation:** França EJ, Magalhães PHM; **Data curation:** França EJ, Magalhães PHM; **Formal Analysis:** Magalhães PHM, Mendes RAS, Barros LR; **Supervision:** Mendes RAS, Barros LR; **Resources:** Mendes RAS; **Writing – original draft:** França EJ; **Writing – review & edition:** França EJ, Mendes RAS, Barros LR; **Final approval:** França EJ.

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