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Morphological description of *Chaetostoma thomsoni*, an endemic fish from Colombia

Descripción morfológica de Chaetostoma thomsoni, especie íctica endémica de Colombia

Descrição morfológica de Chaetostoma thomsoni, um peixe endêmico da Colômbia

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Abstract

Background: The Porce River basin, where the Porce II and Porce III reservoirs are located, harbors a wide diversity of endemic ichthyofauna, many of which lack detailed anatomical and histological descriptions. *Chaetostoma thomsoni* Regan, 1904 (Siluriformes: Loricariidae), commonly referred to as striped rubbernose plecostomus, cucha, or carachama in South America, is a teleost fish that inhabits fast-flowing rivers and streams with moderate slopes. This species is abundant in the Magdalena and Cauca River basins in Colombia. **Objective:** To characterize the anatomical and histological features of the skin and internal organs of *C. thomsoni* from the Porce River basin. **Methods:** Thirty-seven specimens of *C. thomsoni* were collected from streams using electrofishing and cast nets. Fish were euthanized with Eugenol solution (300 mg/L), preserved in 10% buffered formalin, labeled, and stored individually in Falcon tubes. Samples were processed at the Animal Anatomy Laboratory of the University of Antioquia, Colombia, where biometric measurements, dissections, and tissue sampling were performed. **Results:** A complete morphometric analysis was carried out, together with a comprehensive description of the skin and internal anatomy, including macro- and microscopic characterization of the intestine, hepatopancreas, spleen, kidney, urinary bladder, and gonads, among other organs. The findings provide reference data on the health status and applied anatomy of the species, including the identification of an optimal cardiopuncture site for blood sampling. A notable observation was the cephalic kidney, exhibiting a cranially bifurcated morphology partially surrounding the brain. Both cephalic and caudal regions of the kidney contained interstitial hematopoietic tissue and displayed endocrine and immunological functions. In addition, Stannius corpuscles were observed as two distinct nodules in the caudal kidney. **Conclusion:** This anatomical and histological characterization provides a baseline for future studies aimed at advancing the knowledge and conservation of endemic Colombian ichthyofauna.

Keywords: *anatomy; <u>Chaetostoma</u>; electrofishing; endemic species; fish; histology; morphology; morphometry; native species; water reservoir.*

Resumen

Antecedentes: La cuenca del río Porce, donde se localizan los embalses Porce II y Porce III, alberga una amplia diversidad de ictiofauna endémica, gran parte de la cual carece de descripciones anatómicas e histológicas detalladas. *Chaetostoma thomsoni* Regan, 1904 (Siluriformes: Loricariidae), conocido en Suramérica como plecostomo narigudo rayado, cucha o carachama, es un pez teleósteo que habita ríos y quebradas de corrientes rápidas y pendientes moderadas. Esta especie es abundante en las cuencas de los ríos Magdalena y Cauca en Colombia. **Objetivo:** Caracterizar las características anatómicas e histológicas de la piel y los órganos internos de *C. thomsoni* de la cuenca del río Porce. **Métodos:** Se recolectaron 37 ejemplares de *C. thomsoni* en corrientes mediante pesca eléctrica y atarraya. Los peces fueron sometidos a eutanasia con solución de eugenol (300 mg/L), fijados en formalina tamponada al 10%, rotulados y almacenados individualmente en tubos Falcon. Las muestras fueron procesadas en el Laboratorio de Anatomía Animal de la Universidad de Antioquia, Colombia, donde se realizaron mediciones biométricas, disecciones y toma de tejidos. **Resultados:** Se efectuó un análisis morfométrico completo, acompañado de una descripción exhaustiva de la piel y la anatomía interna, con caracterización macro y microscópica del intestino, hepatopáncreas, bazo, riñón, vejiga urinaria y gónadas, entre otros órganos. Los hallazgos proporcionan datos de referencia sobre el estado de salud y la anatomía aplicada de la especie, incluyendo la identificación de un sitio óptimo para la toma de muestras sanguíneas mediante cardiopunción. Un hallazgo relevante fue la morfología del riñón cefálico, con disposición bifurcada cranealmente que rodea parcialmente al encéfalo. Tanto la región cefálica como la caudal del riñón contenían tejido hematopoyético intersticial y presentaban funciones endocrinas e inmunológicas. Además, se observaron corpúsculos de Stannius como dos nódulos diferenciados en el riñón caudal. **Conclusión:** Esta caracterización anatómica e histológica constituye una línea de base para futuros estudios orientados a ampliar el conocimiento y la conservación de la ictiofauna endémica colombiana.

Palabras clave: *anatomia; <u>Chaetostoma</u>; electropesca; embalse; especies nativas; histología; morfología; morfometría; pez; peces endémicos.*

Resumo

Antecedentes: A bacia do rio Porce, onde estão localizados os reservatórios Porce II e Porce III, abriga uma ampla diversidade de ictiofauna endêmica, grande parte da qual carece de descrições anatômicas e histológicas detalhadas. *Chaetostoma thomsoni* Regan, 1904 (Siluriformes: Loricariidae), conhecido na América do Sul como cascudo-de-nariz-riscado, cucha ou carachama, é um peixe teleósteo que habita rios e riachos de corrente rápida e declividade moderada. Esta espécie é abundante nas bacias dos rios Magdalena e Cauca, na Colômbia. **Objetivo:** Caracterizar as características anatômicas e histológicas da pele e dos órgãos internos de *C. thomsoni* da bacia do rio Porce. **Métodos:** Foram coletados 37 exemplares de *C. thomsoni* em cursos d'água por meio de pesca elétrica e tarrafa. Os peixes foram submetidos à eutanásia com solução de eugenol (300 mg/L), fixados em formalina tamponada a 10%, rotulados e armazenados individualmente em tubos Falcon. As amostras foram processadas no Laboratório de Anatomia Animal da Universidade de Antioquia, Colômbia, onde foram realizadas biometria, dissecação e coleta de tecidos. **Resultados:** Foi realizada uma análise morfométrica completa, juntamente com uma descrição abrangente da pele e da anatomia interna, incluindo a caracterização macro e microscópica do intestino, hepatopâncreas, baço, rim, bexiga urinária e gônadas, entre outros órgãos. Os achados fornecem dados de referência sobre o estado de saúde e a anatomia aplicada da espécie, incluindo a identificação de um local ótimo para coleta de sangue por cardiopunção. Um achado relevante foi a morfologia do rim cefálico, com disposição bifurcada cranialmente que envolve parcialmente o encéfalo. Tanto a região cefálica quanto a caudal do rim continham tecido hematopoiético intersticial e apresentavam funções endócrinas e imunológicas. Além disso, foram observados corpúsculos de Stannius como dois nódulos distintos no rim caudal. **Conclusão:** Esta caracterização anatômica e histológica constitui uma linha de base para futuros estudos destinados a ampliar o conhecimento e a conservação da ictiofauna endêmica colombiana.

Palavras-chave: *anatomia; <u>Chaetostoma</u>; espécies nativas; histologia; morfologia; morfometria; peixe; peixes endêmicos; pesca elétrica; reservatório de agua.*

Introduction

Colombia hosts highly diverse aquatic ecosystems with a remarkable richness of endemic species. According to the Colombian Association of Ichthyologists, 419 fish species have been described in the country (Do Nascimiento et al., 2024). Native fish play a critical role in the biodiversity of freshwater ecosystems, serving not only as food for riparian communities but also as an essential protein source for numerous animal species (Restrepo et al., 2022). Nevertheless, this ichthyofauna is increasingly threatened by anthropogenic pressures, including extensive livestock production, agriculture, introduction of exotic species (Chará, 2002), and illegal activities such as mining, which releases pollutants into aquatic environments (Mancera-Rodríguez & Álvarez-León, 2006). Additionally, hydroelectric dams disrupt natural ecosystems, directly altering the reproductive cycles of many endemic fish (Jiménez-Segura et al., 2014a). The progressive decline of biodiversity in freshwater systems underscores the importance of conducting studies on these environments and their native fish communities.

The Porce River originates in the eastern massif of Antioquia province, at Alto de San Miguel, south of Medellín, at an altitude of approximately 2,660 meters above sea level. It flows northeast across central Antioquia before joining the Nechí River, a tributary of the Cauca River. From its source to its passage through Barbosa (Antioquia), at 680 meters above sea level, it is known as the Medellín River; downstream from this point, it is referred to as the Porce River (Loaiza et al., 2018).

The Porce River basin and its reservoirs (Porce II and Porce III) host both endemic and introduced fish. Introduced species include *Oreochromis niloticus*, *Xiphophorus hellerii*, and *Poecilia reticulata* (Huertas et al., 2022), while endemic taxa comprise *Chaetostoma spp.*, *Saccodon spp.*, *Parodon spp.*, *Astyanax spp.*, and *Brycon henni* (Jiménez-Segura et al., 2014). Although introduced species have been extensively studied, most endemic species lack morphometric, anatomical, and histological characterization.

Anatomical studies are crucial for understanding the physiological baseline of fish species. Gonadal anatomy provides insights into reproductive physiology, which is fundamental for ecosystem preservation. This physiology is strongly influenced by environmental conditions (Rodríguez & Carrillo, 2001; Pankhurst & Munday, 2011). Furthermore, the anatomical and histological assessment of organs such as the gills and liver is widely employed for detecting the impact of aquatic pollution, as these are primary targets of waterborne contaminants (Torres et al., 2010; Malik et al., 2020).

Chaetostoma thomsoni Regan, 1904 (Siluriformes: Loricariidae) is a teleost fish commonly known as an armored catfish with a ventral sucker mouth, typical of tropical environments (ITIS, 2024). The species is distributed in fast-flowing rivers and streams with water temperatures of 20–22 °C, moderate slopes, rocky substrates, and abundant periphytic vegetation in the Magdalena, Cauca, Sinú, and Cesar river basins (Lasso et al., 2011; Restrepo-Santamaria et al., 2022).

Populations of *C. thomsoni* are currently considered stable, and the species is classified as Least Concern on the IUCN Red List of Threatened Species (Jiménez-Segura et al., 2016). It is an important food resource for riparian communities and displays herbivorous, detritivorous, and algivorous feeding habits. Its specialized mouthparts allow attachment to rocky substrates while grazing on algae and detritus (Zúñiga-Upegui, 2005; Maldonado-Ocampo et al., 2005). Morphologically, *C. thomsoni* is described as a brownish fish with small spots on the fin rays, a body depth smaller than its standard length, and a head size three times larger than body. Each operculum bears 4–5 odontodes, and the scaleless body is dorsally covered by 24–25 bony plates (Regan, 1904; Reis et al., 2003; Jiménez-Segura et al., 2014).

To date, descriptions of *C. thomsoni* have been limited to external morphology for taxonomic purposes and ecosystem monitoring. However, no detailed anatomical or histological analyses of the skin and internal organs are available. Such knowledge is essential for understanding species biology, ecological interactions, and adaptive processes. The present study provides the first anatomical and histological description of the skin and internal organs of *C. thomsoni* inhabiting the Porce River basin.

Materials and methods

Ethical approval

All procedures were conducted in compliance with the Ethics and Animal Experimentation Committee of the University of Antioquia. The study was endorsed under protocol No. 138 (February 9, 2021) within the framework of the project "*Respuesta de la Ictiofauna a la formación de embalses en los Andes Colombianos*". Authorization to transport biological diversity specimens was granted by the National Authority of Environmental Licenses (ANLA).

Study area

Fieldwork was conducted in the Porce River basin, within the influence zone of the Porce II and Porce III reservoirs, located in northwestern Antioquia. Specimens were collected from tributary streams distributed across the municipalities of Amalfi, Anorí, Gómez Plata, and Santa Rosa de Osos (Figure 1). These streams are characterized by slight to moderate slopes, sandy and eroded margins, muddy substrates, and abundant riparian vegetation. Waters originate from the Guadalupe waterfall near Puente Acacias, where the discharge of the Porce II reservoir joins the Porce River and flows downstream to the Porce III reservoir.

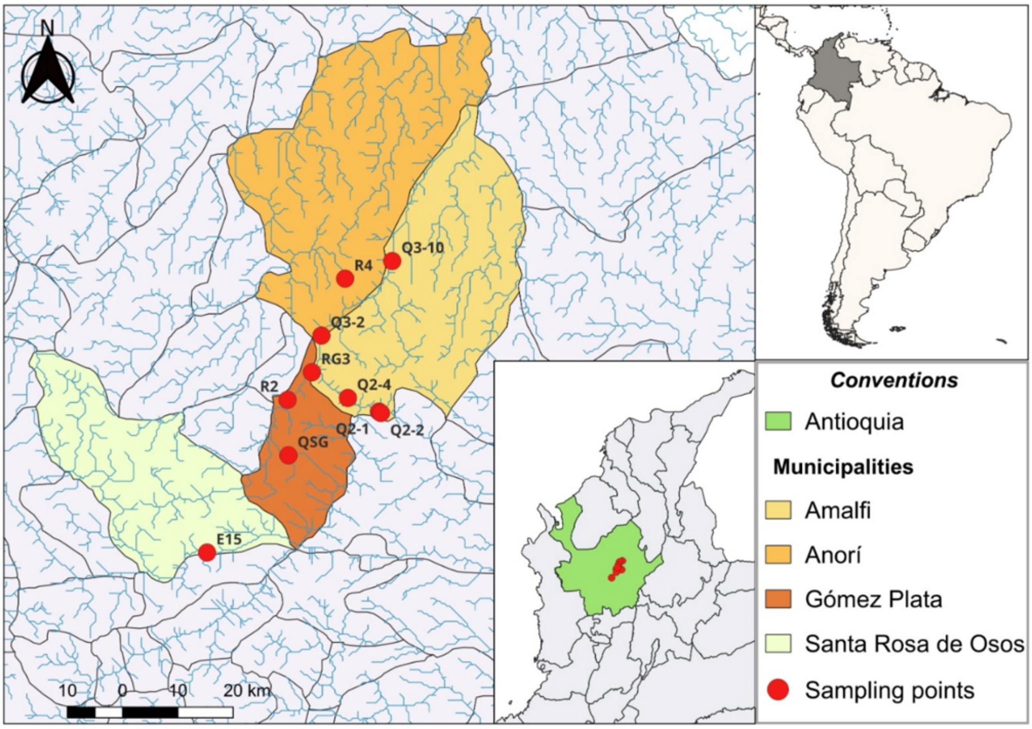

Figure 1. Map of sampling areas in Antioquia province, Colombia. The red points correspond to the sampling locations where fish were captured. Q2-1 Canana stream, R2 Guadalupe River after discharge, Q3-10 El Boquerón stream, Q2-4 Picardía stream, Q2-2 Cancana stream mouth, R4 Porce III reservoir, Q3-2 El Saíno stream, QSG Santa Gertrudis stream, E15 Río Grande (Mocorongo), RG3 Guadalupe River.

Fish collection

Sampling was performed between April 2022 and April 2023 using electrofishing and cast nets. At each site, a 100 m stretch of the watercourse was surveyed, targeting individuals of *Chaetostoma thomsoni* (n = 37). For each specimen, taxonomic identification, collection site, date, and biometric measurements—length, height, weight, and external description—were recorded.

Euthanasia was carried out by immersion in Eugenol (300 mg/L). Specimens were fixed in 10% buffered formalin by intratissue injection (1 mL syringe, 25 Ga ½ inch needle) followed by immersion in Falcon-type containers (screw cap) or resealable bags for larger individuals. Samples remained in fixative for at least one week prior to transfer to the Animal Anatomy Laboratory of the University of Antioquia.

Laboratory procedures

Biometry and external morphology

Biometric measurements were obtained using a digital balance (MH-200 pocket scale) and an analytical balance (ADAM PW 124). Linear morphometrics were measured with a digital Vernier caliper (Uyulstools CLD006). Based on total length (TL), specimens were classified as juveniles (< 70 mm, without gonadal development) or adults (> 70.1 mm). Data were stored in Microsoft Excel for subsequent analyses.

Each specimen was placed in a dissection tray for detailed morphometric assessment. Total length (mouth to caudal-fin tip) and preserved weight were recorded. Morphometric evaluation included counts of dermal plates along three regions (head to dorsal fin, dorsal to adipose fin, and anal to caudal fin). In the head region, measurements included total length, width, height, and counts of odontodes on the opercula and rostral margin.

The trunk region was measured from the operculum to the urogenital pore, with lengths of pectoral and pelvic fin spines and counts of spines and soft rays. Dorsal fin height and length were recorded along with spine and ray counts, and the adipose fin was examined for the presence of a supporting spine.

The caudal region was measured from the anal pore to the caudal-fin tip, including caudal peduncle length. Measurements of the anal and caudal fins followed the same criteria, documenting length, spines, and rays.

Dissection and tissue sampling

Specimens were dissected using conventional and entomological tools (scalpel no. 10 blade with no. 3 handle, clawless forceps, and Metzenbaum scissors). A ventral midline incision extended from the caudal margin of the oral disc to 2 mm cranial to the urogenital pore, exposing the coelomic cavity. Structures were observed under a stereoscope (Nikon SMZ-1). Tissue samples were preserved in wide-mouth glass or plastic jars, labeled with specimen and organ identification. Smaller samples were mounted on absorbent paper, labeled in pencil, and sealed with staples.

Reproductive stages

Oocyte development in *C. thomsoni* was categorized into three stages following Loaiza et al. (2018): (a) stage III, mature/pre-spawning oocytes > 2 mm in diameter; (b) stage II, oocytes 1–2 mm in diameter; and (c) stage I, oocytes < 1 mm in diameter. The species exhibits asynchronous ovarian development, consistent with multiple spawning events per reproductive season (Sierra-de la Rosa, 2007).

Histology

Formalin-fixed tissues were processed at the Pathology Laboratory of the University of Antioquia. For integumentary analysis, carcasses were decalcified in 10% nitric acid for 24 h, followed by serial longitudinal (n = 3) or transverse (n = 2) sectioning. Tissues were processed using an automated tissue processor (Thermo Excelsior AS500), dehydrated in graded ethanol (70–100%), cleared in xylene, embedded in paraffin, sectioned at 4 µm (Microm HM325, Thermo Scientific), and stained with hematoxylin and eosin. Slides were examined under light microscopy (Olympus BX53).

Image acquisition

External morphology and dissections were documented photographically with a Nikon D5500 camera. Additional stereoscopic images were obtained using Nikon SMZ-1 and Olympus SZ2-ILST stereoscopes, and micrographs were taken with an Olympus BX53 microscope equipped with an adapted digital camera.

Data analysis

Descriptive statistics (mean and standard deviation) were applied to all morphometric variables using Microsoft Excel.

Results

Sampling and capture of C. thomsoni

A total of 70 ichthyofauna sampling sites were surveyed within the study area. Specimens of *C. thomsoni* were recorded at only 10 sites, corresponding to 16.6% of the total, with 37 individuals collected (Table 1).

Table 1. Location and number of captured specimens.

Point	Station	Longitude	Latitude	Altitude (masl)	N
Q2-1	Canana Ravine above (bridge)	-75.0802W	6.7745N	991.8	7
R2	Guadalupe River after download	-75.2296W	6.7937N	1692.4	1
Q3-10	Boquerón Ravine	-75.0584W	7.0292N	363.1	9
Q2-4	Picardía Ravine	-75.1310W	6.7968N	943.0	2
Q2-2	Cancana Ravine	-75.0769W	6.7721N	941.1	7
R4	Porce III Dam (limnim)	-75.1355W	6.9920N	555.6	3
Q3-2	El Saíno Ravine (La Unión)	-75.1742W	6.8989N	700.5	1
QSG	Santa Gertrudis Ravine	-75.2282W	6.7029N	1142.1	4
E15	Grande River (after download-Mocorongo)	-75.3612W	6.5438N	1792.5	2
RG3	Guadalupe River	-75.1897W	6.8388N	806.6	1

A total of 37 specimens of *C. thomsoni* were obtained, all from the Porce River basin. The highest representation was recorded in the Canana, El Boquerón, and Cancana streams, which together accounted for 62.16% of the individuals, indicating a higher local abundance of the species in these areas. Anatomical and histological examinations were performed, comprising external (n = 37) and internal descriptions (n = 18). The main findings are presented below.

External morphometry

For the morphometric analysis, specimens were classified into two groups according to body size and gonadal development (Table 2). Juveniles were defined as individuals <70 mm in total length, with no evidence of gonadal development, whereas adults were >70 mm in total length and exhibited gonadal development. Juveniles had a mean body weight of 2.91 g, approximately eight times lower than that of adults (23.01 g), a difference largely attributable to gonadal size, given that the species exhibits a gonadosomatic index of ~10%. Mean total length in juveniles was 60.26 mm, representing two-thirds of the adult mean (99.39 mm). Mean body width was 8.30 mm in juveniles and nearly doubled in adults (15.52 mm), consistent with the lateral expansion associated with gonadal maturation.

Table 2. External morphometry of *Chaetostoma thomsoni* specimens.

Parameter	Juveniles (n=12) Media ± SD	Adults (n=25) Media ± SD
Live weight (g)	2.91 ± 0.98	23.01 ± 20.58
Fixated specimen weight (g)	3.52 ± 1.13	20.95 ± 18.46
Total length (mm)	60.26 ± 5.95	99.39 ± 20.30
Standard length (mm)	49.44 ± 5.45	84.62 ± 17.83
Total height (mm)	8.30 ± 1.18	15.52 ± 3.85
Number of body plates on dorsal view	23.08 ± 1.24	24.04 ± 1.46
Number of plates between head to dorsal fin	3.67 ± 0.49	3.96 ± 0.20
Number of plates between dorsal and adipose fins	14.33 ± 1.56	13.68 ± 0.95
Number of plates between anal and caudal fins	12.83 ± 0.94	11.88 ± 1.92

Morphometric analyses were conducted systematically by anatomical region. In the head, dorsal length and width were nearly identical, producing a square-shaped morphology (Table 3). Odontode counts on the opercula and adjacent cranial surfaces indicated that odontode number is not strictly determined by age or body size, as these structures—composed of dentin—are readily lost. Odontodes of varying sizes were observed in both juveniles and adults, suggesting the capacity for regeneration, analogous to the replacement of dentin-based scales in teleosts. Head proportions scaled consistently with overall body size.

Table 3. Morphometric measurements of the head region in *Chaetostoma thomsoni* specimens.

Parameter	Juveniles (n=12) Media ± SD	Adults (n=25) Media ± SD
Dorsal length (mm)	15.29 ± 1.44	25.29 ± 4.63
Dorsal width (mm)	13.59 ± 1.38	25.13 ± 6.44
Ventral length (mm) from opercula to mouth	8.83 ± 1.27	16.65 ± 6.75
Height (mm)	7.30 ± 0.76	13.27 ± 3.65
Head proportion (height/length)	0,47	0,52
Number of odontodes right opercula	4.33 ± 1.61	5.16 ± 1.37
Number of odontodes left opercula	4.08 ± 1.56	4.56 ± 1.56
Number of odontodes cranial to right opercula	2.75 ± 1.14	3.52 ± 1.66
Number of odontodes cranial to left opercula	2.92 ± 1.00	3.92 ± 1.29

In the trunk region, pectoral and pelvic fins exhibited equivalent lengths in both juveniles and adults. Morphometric analysis revealed that the growth rate of the hard ray in these fins was approximately twice as great in adults as in juveniles. In the dorsal fin, the length of the hard ray was proportionate to the fin height when fully extended, producing an isosceles triangle configuration. The adipose fin contained a hard ray and only minimal, weakly developed soft tissue in its macroscopic structure. Relative to trunk length, the proportion of hard ray size increased with maturity in most fins, except for the dorsal and adipose fins, which remained proportionally more prominent in juveniles (Table 4).

Table 4. External morphometry of the trunk region in *Chaetostoma thomsoni* specimens.

Structure	Parameter	Juveniles (n=12) Media ± SD	Adults (n=25) Media ± SD
Trunk region	Total size (mm)	17.09 ± 2.40	30.12 ± 7.32
Right pectoral fin	Hard fin ray length (mm)	11.44 ± 1.92	22.31 ± 5.86
	Number of hard fin rays	1.00	1.00
	Number of soft fin rays	5.08 ± 0.29	5.4 ± 0.50
	Pectoral fin proportion*	0.66	0.74
Left pectoral fin	Hard fin ray length (mm)	11.80 ± 1.83	23.04 ± 5.73
	Number of hard fin rays	1.00	1.00
	Number of soft fin rays	5.00	5.46 ± 0.59
	Pectoral fin proportion*	0.69	0.76
Dorsal fin	Hard fin ray length (mm)	9.94 ± 1.93	17.08 ± 4.41
	Height (mm)	9.71 ± 1.25	17.53 ± 4.79
	Length (mm)	14.80 ± 2.25	28.56 ± 6.73
	Number of hard fin rays	1.00	1.00
	Number of soft fin rays	7.92 ± 0.29	7.96 ± 0.45
	Dorsal fin proportion*	0.58	0.56
Right pelvic fin	Hard fin ray length (mm)	10.63 ± 1.55	19.56 ± 5.33
	Number of hard fin rays	1.00	0.96 ± 0.20
	Number of soft fin rays	4.42 ± 0.51	4.76 ± 0.83
	Pelvic fin proportion*	0.62	0.64
Left pelvic fin	Hard fin ray length (mm)	10.46 ± 1.83	19.67 ± 4.70
	Number of hard fin rays	1.00	1.00
	Number of soft fin rays	4.42 ± 0.51	4.92 ± 0.28
	Pelvic fin proportion*	0.61	0.65
Adipose fin	Hard fin ray length (mm)	4.11 ± 0.84	6.71 ± 1.54
	Number of hard fin rays	1.00	1.00
	Number of soft fin rays	0.00	0.00
	Adipose fin proportion*	0.24	0.22

*All fin proportions were based on total trunk length (mm).

In the caudal region, the tail fin exhibited a homocercal, emarginated morphology. The ventral hard radius was consistently larger than the dorsal one, with an average difference of approximately 2 mm in juveniles and 4 mm in adults (Table 5).

Table 5. External morphometric measurements of the caudal region in *Chaetostoma thomsoni* specimens.

Structure	Parameter	Juveniles (n=12) Media ± SD	Adults (n=25) Media ± SD
Caudal region	Total size (mm)	32.45 ± 3.27	56.77 ± 12.17
	Caudal peduncle size	5.44 ± 1.96	8.06 ± 6.42
	Caudal peduncle proportion*	0.16	0.14
Anal fin	Hard fin ray length (mm)	4.96 ± 0.98	7.72 ± 2.22
	Number of hard fin rays	1.00	1.00
	Number of soft fin rays	4.00 ± 0.43	4.04 ± 0.20
Caudal fin	Dorsal hard fin ray length (mm)	10.49 ± 1.79	18.30 ± 5.37
	Ventral hard fin ray length (mm)	12.25 ± 2.92	22.74 ± 6.06
	Number of hard fin rays	2.00	2.00
	Number of soft fin rays	13.33 ± 0.65	14.08 ± 0.57
	Ventral hard fin proportion**	0.24	0.26

*The proportion of the caudal peduncle was determined relative to the length of the caudal region (measured from the urogenital pore to the distal tip of the caudal fin).

**The proportion of the ventral hard ray of the caudal fin was determined relative to the standard body length (measured from the snout tip to the caudal peduncle).

Anatomical description of C. thomsoni

Head region

C. thomsoni exhibits a broad, permanently open mouth located ventrally, accounting for more than 60% of the head region. The mouth is equipped with two prominent lips and paired barbels (Figure 2A). The upper lip functions as a mobile, muscular structure that contributes to locomotion, whereas the lower lip is larger, less muscular, and specialized as a suction cup with numerous spherical papillae that facilitate adhesion to the substrate (approximately 53 papillae/cm^2). Under stereoscopic observation, the dentition of *C. thomsoni* resembles a brush composed of four orderly rows of bristle-like teeth, which are used to scrape food from hard rock surfaces. No evidence of tooth loss or irregular spacing was detected, indicating high durability of the dental structures. The teeth present pigmented modifications at their apex or free margin, conferring a metallic and hardened appearance (Figure 2B).

In the rostrodorsal portion of the head, the nasal openings (nares) are situated in a rostromedial position relative to the eye. Each nare consists of two small depressions, approximately 2 mm in diameter, partially covered by a mobile membrane. The central region of this membrane contains an aperture that leads to a short, 1.5 mm rostrocaudally oriented channel ending in a blind sac. Additionally, the membrane completely covers a second channel of equal length oriented in the opposite (caudorostral) direction.

The eyes are positioned in the caudal and lateral third of the head, bordered by a dashed line of light spots. Measurements in a representative adult specimen revealed a rostrocaudal diameter of 6 mm and a dorsoventral diameter of 5 mm. The pupil is crescent-shaped, outlined by punctate light pigmentation. Eye mobility was observed along the dorsoventral axis (Figure 2C).

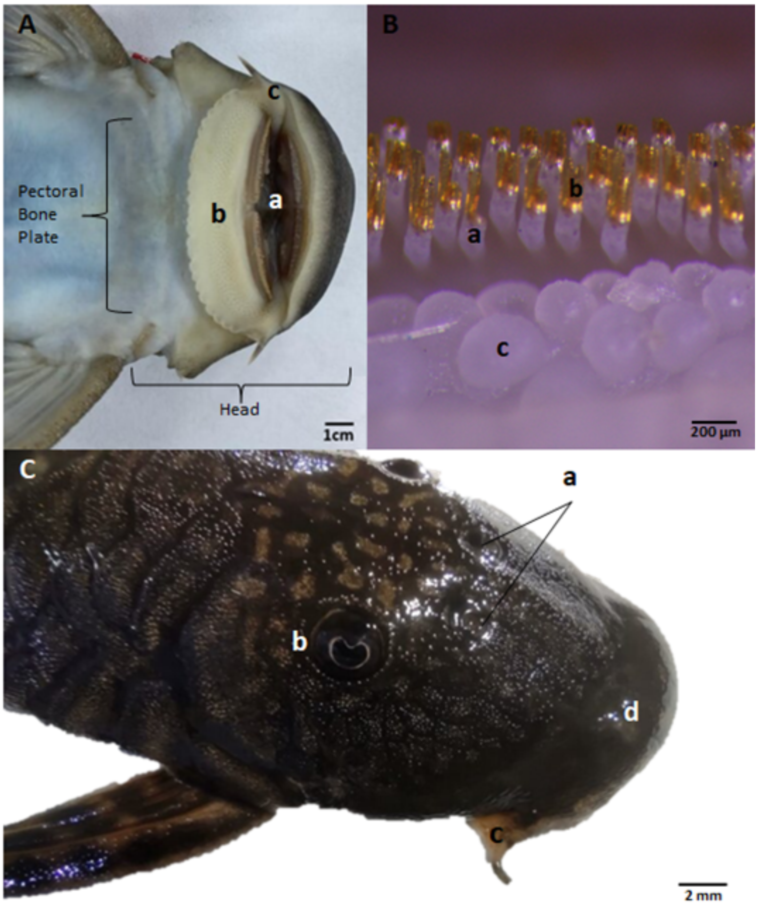

Figure 2. Morphological features of the head region in *Chaetostoma thomsoni*. A) Ventral view: (a) oral cavity, (b) labial sucker cup, (c) barbels. B) Mandible: (a) teeth, (b) pigmented structures of teeth, (c) papillae of the lip sucker cup. C) Dorsal view: (a) nares, (b) eye, (c) barbels, (d) upper lip.

Trunk and caudal regions

In the trunk and caudal regions, the integument exhibited bony plates bearing spiny projections, extending even to the fins. The fins showed pigmented conical elements associated with the hard rays, while linear pigment deposits were present along the soft rays (Figure 3A). Histological examination of the fins revealed the bony structure of each soft ray, bordered by melanophores and interspersed with connective tissue (Figure 3B). The dorsal integument displayed numerous bony plates with craniocaudally oriented spiny projections (Figure 3C). Microscopically, the dermal bone was organized into overlapping placodes, whereas the epidermis was disrupted by conical projections emerging from the bony plates (Figure 3D). These correspond to the spiny projections described macroscopically (Figure 3C).

The epidermis comprised 5–7 cellular layers. Goblet cells were identified in the middle stratum. Cells of both the basal and middle layers were arranged in a palisade pattern, consisting of cuboidal elements oriented perpendicularly. The basal membrane contained abundant diffuse melanin deposits, underlain by a thin dermis and a compact bony layer (Figure 3E).

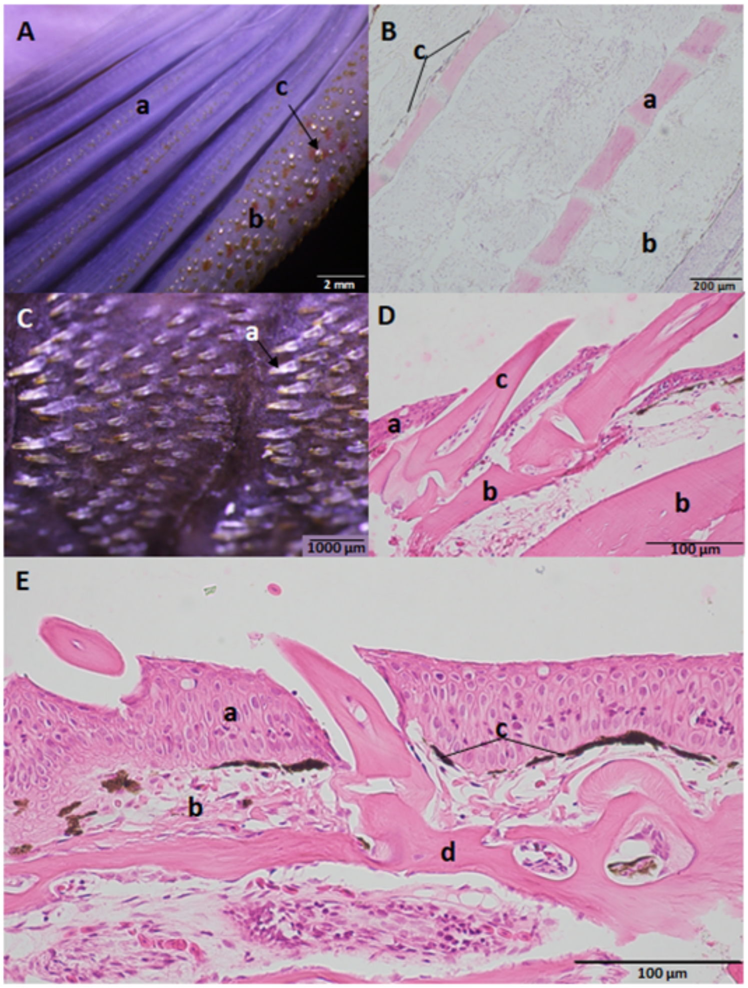

Figure 3. Fins and dorsal integument of the trunk and caudal regions in *Chaetostoma thomsoni*. A) Pectoral fin: (a) soft ray, (b) hard ray (spine), (c) pigmented conical projection. B) Histological section of the pectoral fin (10X): (a) soft ray, (b) connective tissue, (c) melanophores. C) Dorsal skin: (a) spiny projections arising from the bony plate. D) Histological section of dorsal skin (40X): (a) epidermis, (b) cutaneous placodes, (c) projections emerging from placodes through the epidermis. E) Histological section of dorsal skin (40X): (a) epidermis, (b) dermis, (c) melanophores, (d) compact bone. Histological sections stained with hematoxylin and eosin (H&E).

Dissection and internal anatomy description

During dissection, the ventral skin was removed, exposing the underlying musculature, which included the pectoral, abdominal, and pelvic muscle groups (Figure 4A). Removal of these muscles provided access to the coelomic cavity, where both pectoral and pelvic bony plates were observed, articulated with their respective fins. Beneath the pectoral bony plates, the heart was identified within its pericardial sac, positioned medially. On either side, the heart was flanked by the gills, each consisting of five arches that occupied a relatively reduced space within the coelomic cavity. Following separation of the gill arches from the cavity, a bony lamina was noted on each side, extending dorsolaterally around the heart, functionally comparable to an operculum. The cardiac morphology revealed the ventricle located caudally and the atrium situated cranially (Figure 4C).

Figure 4. Dissection of the ventral skin and coelomic cavity in *Chaetostoma thomsoni*. A) Ventral musculature exposed: (a) pectoral fins, (b) pelvic fins, (c) anal fin, (d) pectoral musculature, (e) pelvic musculature, (f) abdominal musculature, (g) urogenital and anal pore. B) Anatomical site for cardiopuncture used in blood sampling; the needle is directed toward the ventricle. C) Coelomic cavity, ventral view: (a) heart (ventricle), (b) gills, (c) opercular bony plates, (d) small intestine arranged in a spiral around the (e) hepatopancreas.

Cardiopunction site

In *C. thomsoni*, conventional blood collection methods used in other teleosts are not feasible due to the ventral position of the operculum, the presence of bony plates enclosing the cardiac cavity, and the dermal ossifications covering the dorsal body surface. Considering the anatomical position of the heart, the cardiopuncture site for blood sampling was precisely located along the ventral midline, caudal to the lower lip and cranial to the pectoral bony plate, with the needle inserted at an angle of approximately 45° (Figure 4B).

Celomic cavity organs

A short, straight esophagus was located dorsal to the heart, between the right and left gill arches, and continued posteriorly into a well-defined U-shaped stomach. This organ, usually empty, was positioned in the right dorsal region adjacent to the small intestine. The small intestine, located caudal to the pectoral bony plate in the caudoventral region, occupied more than 50% of the coelomic cavity and was arranged in a spiral surrounding a central parenchymal, greenish structure (Figure 5A). Histological analysis identified this structure as the hepatopancreas (Figure 5B), characterized by the presence of both hepatocytes and pancreatic islets. The hepatopancreas displayed a multilobed configuration, with six lobes situated within the intestinal spiral (Figure 5C) and two additional lobes located centrally, one dorsally (Figure 5D) and one ventrally (Figure 5E).

The large intestine and rectum extended in a nearly straight course toward the urogenital pore. Although the distinct portions of the small intestine were not clearly differentiated, the junction between the small and large intestine was identifiable both macroscopically and histologically. As in other teleosts, the coelomic cavity was lined by a simple pigmented squamous epithelium covering the internal wall, terminating cranial to the urogenital orifice. Fine interwoven fibers of connective tissue supporting adipose deposits were observed throughout the cavity, surrounding the organs of the digestive tract.

When the visceral package was lifted, a ligament anchoring it to the dorsocranial wall of the coelomic cavity was evident. From a dorsal view, the esophageal opening was observed in the craniomedial region of the coelomic cavity. In the craniodorsal left region, two distinct brown structures were identified: a lateral triangular organ corresponding to the spleen (Figure 5F) and a medial tongue-shaped portion of the hepatopancreas. Histological evaluation of the spleen revealed clear differentiation between red and white pulp, as well as the presence of the central arteriole (Figure 5G). A ligament connected these structures ventrally to the intestinal spiral. Additionally, a lymph node was observed embedded in the adipose tissue surrounding the caudal portion of the greater curvature of the stomach.

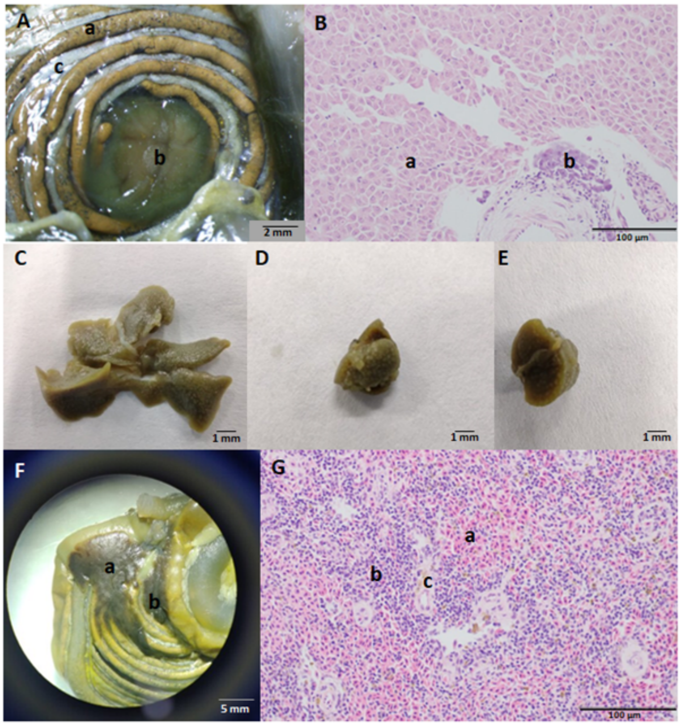

Figure 5. Hepatopancreas and spleen of *Chaetostoma thomsoni*. A) Small intestine arranged in a spiral around a portion of the hepatopancreas. (a) Small intestine, (b) Hepatopancreas, (c) Adipose tissue. B) Histological section of the hepatopancreas, 40×. (a) Hepatocytes, (b) Pancreatic islets. C) Multilobed structure of the hepatopancreas in dorsal view. D) Additional hepatopancreatic lobe located dorsally. E) Additional hepatopancreatic lobe located ventrally. F) Stereomicroscopic image of the spleen in dorsal view. (a) Spleen, (b) Hepatopancreas. G) Histological section of the spleen, 40×. (a) Red pulp, (b) White pulp, (c) Central arteriole. Histological preparations are stained with H&E.

The stomach presented a distinct lesser and greater curvature, with translucent walls that permitted visualization of the gastric contents. The proximal segment of the small intestine, the duodenum, followed a defined trajectory: originating at the pylorus, it extended cranially as the ascending duodenum, formed a cranial flexure situated dorsocranial to the stomach, and continued caudally along the left margin as the descending duodenum. Subsequently, it crossed to the right side in close association with the greater curvature of the stomach, forming a caudal flexure, before extending caudally to give rise to the intestinal spiral. This spiral followed a counterclockwise disposition (Figure 6). Dissection of the spiral revealed centripetal coils in the initial portion, followed by centrifugal coils, tentatively corresponding to the jejunum and ileum, with adipose tissue interposed between adjacent loops. The terminal portion of the spiral differentiated macroscopically into a thicker tubular segment, identified as the large intestine, oriented dorsocaudally to the left and projecting medially in its caudal course to terminate in the rectum.

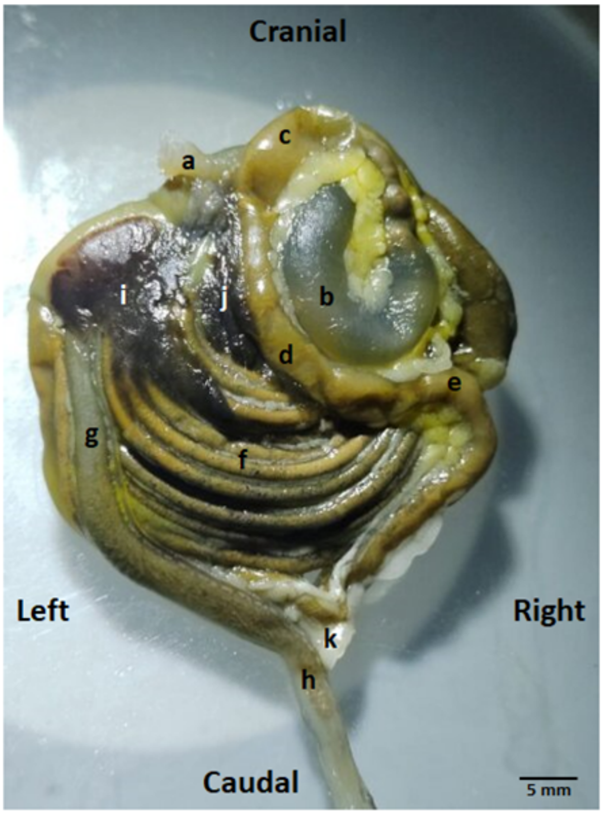

Figure 6. Dorsal view of the viscera within the coelomic cavity of *Chaetostoma thomsoni*. (a) Esophagus, (b) Stomach, (c) Cranial duodenal flexure, (d) Duodenum, (e) Caudal duodenal flexure, (f) Jejunum and ileum, (g) Large intestine, (h) Rectum, (i) Spleen, (j) Hepatopancreas, (k) Perivisceral adipose tissue.

Gonads

Dorsally to the intestine, the gonads were observed, sac-like in shape, fused caudally at the midline near the genital pore. In male specimens, they exhibited a cranial apex with a thickening in the middle third. Two elongated yellowish structures were present on each side, histologically corresponding to the testes (Figure 7A). Additionally, in the midportion, two other translucent whitish blind sacs were identified, which histologically corresponded to the ureters.

In reproductively active females, the gonads presented oocytes distributed along the dorsal region of the coelomic cavity (Figure 7B), slightly wider at the trunk level (Figure 7C). The suspensory ligament of the ovary (mesovarium) was also evident, supporting the gonad along its entire length to the dorsal wall of the coelomic cavity (Figure 7D), as well as the interovarian ligament, which connected the gonads at the caudal two-thirds level. Oocytes were classified into three developmental stages: (a) stage III or pre-spawning oocytes, with a diameter > 2 mm; (b) stage II oocytes, with a diameter of 1–2 mm; and (c) stage I oocytes, with a diameter < 1 mm (Figure 7E).

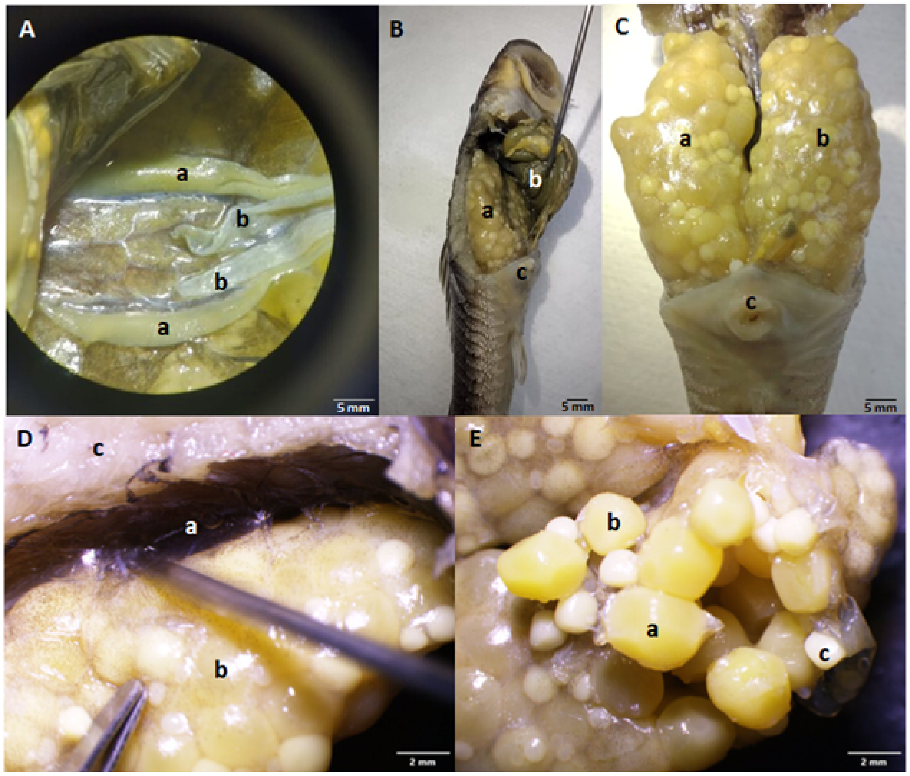

Figure 7. Gonads of *Chaetostoma thomsoni*. A) Male genital organs located in the dorsomedial region at the mid-third of the coelomic cavity. (a) Testes, (b) Ureters. B) Female gonads in reproductive phase, right lateral view. (a) Ovaries with oocytes, (b) Visceral package, (c) Urogenital pore. C) Ventral view showing the spatial distribution of the gonads within the coelomic cavity. (a) Right ovary with oocytes, (b) Left ovary with oocytes, (c) Urogenital pore. D) Lateral view of the ovary. (a) Suspensory ligament (mesovarium), (b) Ovary with oocytes, (c) Dorsal wall of the coelomic cavity. E) Oocytes at different stages of development. (a) Stage III oocyte, (b) Stage II oocyte, (c) Stage I oocyte.

Kidney and urogenital pore

As in other teleosts, in *Chaetostoma thomsoni* the caudal kidney is located in the cranial two-thirds of the coelomic cavity roof, ventral to the vertebral column. At the level of the Stannius corpuscles, the caudal kidney extends deeper into the connective tissues covering the ventral surface of the vertebral column. Lateral to the kidney, the ureters were observed, forming cranially blind sacs and caudally converging into the urinary bladder, which opened into the urogenital pore (Figure 8A). A translucent membranous layer covers the kidney, the Stannius corpuscles, and the ureters. Histologically, the caudal kidney exhibited abundant interstitial hematopoietic tissue, consistent with that described in other teleosts (Figure 8B).

The cephalic kidney was identified through serial histological cross-sections of decalcified skulls. It exhibited four lobes separated by bony tissue: two dorsal and two ventral, with the ventral lobes being larger. Similar to the caudal kidney, abundant interstitial hematopoietic tissue was observed (Figure 8C).

Finally, the exploration of the urogenital pore revealed the presence of two openings: a cranioventral one, leading into the intestine and thus identified as the anal pore, and a dorsocaudal one, which received the gonadal ducts and communicated with the urinary bladder, thereby identified as the urogenital pore (Figure 8D).

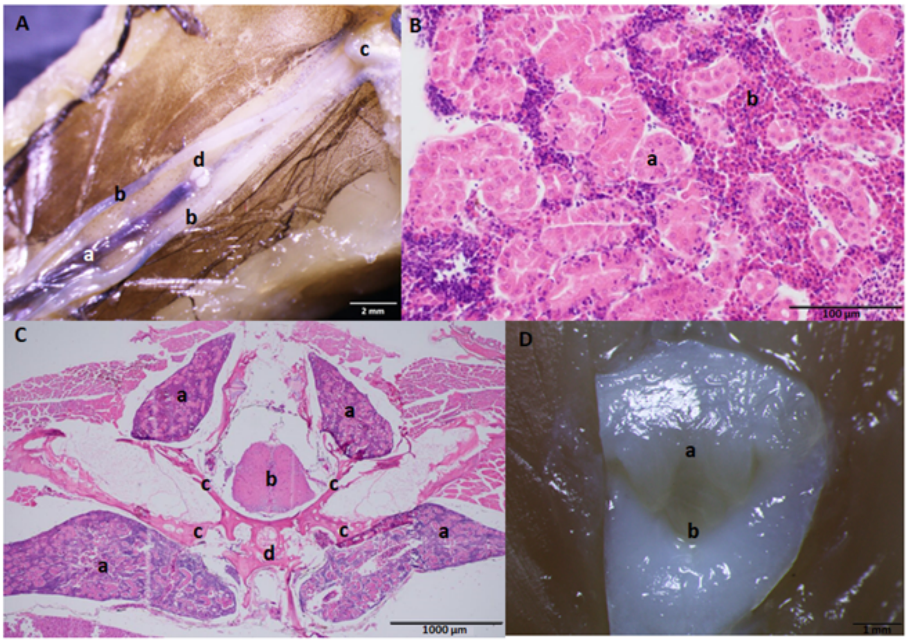

Figure 8. Kidney and urogenital pore of *Chaetostoma thomsoni*. A) Ventral view of the roof of the coelomic cavity. (a) Caudal kidney, (b) Ureters, (c) Urinary bladder, (d) Stannius corpuscles. B) Histology of the caudal kidney, 40X. (a) Renal tubules, (b) Interstitial hematopoietic tissue. C) Histology of the cephalic kidney, 4X. (a) Cephalic kidney with interstitial hematopoietic tissue, (b) Brain, (c) Cranial bone, (d) Vertebral bone. D) Ventral view of the pelvic region showing the anal and urogenital pores. (a) Anal pore, (b) Urogenital pore. Histological preparations are stained with H&E.

Discussion

Four species of Loricariidae have been reported in the Porce River basin: *Chaetostoma fischeri, C. leucomelas, C. thomsoni*, and *Lasiancistrus caucanus* (Jiménez-Segura et al., 2014; Restrepo-Santamaría, 2022). The present study confirms that *C. thomsoni* is one of the most abundant representatives of this genus in the basin, consistent with previous observations (Restrepo-Santamaría, 2022). Ten distribution points were identified in the Porce River, a sub-basin of the Magdalena River, indicating that the species remains well established in this area.

This study constitutes the first integrative morphological description of *C. thomsoni*, encompassing both external and internal anatomy as well as histology. In the absence of previous reports on this species, our discussion draws on comparative data from other Loricariidae. This family is among the most diverse Neotropical catfishes also known as silurids (Reis et al., 2003) and is characterized by morphological adaptations that confer ecological plasticity and tolerance to diverse thermal habitats (Favré, 1978).

Fish of the Loricariidae family are characterized by a dorsoventrally flattened body. Additionally, they have bony plates that completely or partially cover the body. In the former case, the plates cover both the dorsal and ventral aspects of the body, as seen in species like *C. Patiae, C. marginatum,* and *C. leucomelas* (Fowler, 1945; Regan, 1904; Eigenmann, 1918). These plates provide the fish with an armored structure, enabling adaptation and tolerance to habitats with rocky bottoms and swift currents. In the latter case, the plates only cover the dorsal side, leaving the belly unprotected and covered by a thin layer of skin, usually whitish in color (Maldonado-Ocampo et al., 2005). This arrangement of plates, also exhibited by *C. thomsoni*, is shared by another species in the same genus, *C. anale* (Fowler, 1943), and by other genera within the same family, such as *Ancistrus triradiatus* (Galvis et al., 1997) and *Lasiancistrus caquetae* (Fowler, 1945). This characteristic is considered an adaptation within the Loricariidae family rather than a specific feature of the genus *Chaetostoma*.

According to the genus, there are some differences in the organization of the bony plates, as they may be arranged in two rows of plates, as seen in *Farlowella gracilis* (Regan, 1904), or in more than two rows, as is the case with *Cordylancistrus daguae* (Eigenmann, 1912; Maldonado-Ocampo et al., 2005). In line with the reported literature, the present study identified more than two rows of bony plates in *C. thomsoni*. The number of plates also varies among genera; in *C. thomsoni*, it falls within the range of 24-25 plates, a quantity similar to that described for other *Chaetostoma* species such as *C. marginatum* (Regan, 1904; Eigenmann, 1922), *C. brevilabiatum* (Dahl, 1942), and *C. vagum* (Fowler, 1943). It is also consistent with the number observed in species from other genera, such as *Ancistrus triradiatus* (Galvis et al., 1997). Both the organization and the quantity of bony plates are important morphological characteristics for the taxonomic determination of species based on external morphology (Maldonado-Ocampo et al., 2005).

The Loricariidae family holds significant importance in the global aquarium trade. Some of these species are widely traded for aquarium purposes in Asian and South American countries, including *Pterygoplichthys punctatus* (spotted pleco), *Leporacanthicus* galaxias (vampire pleco), *Baryancistrus demantoides* (yellow-green pleco), and *C. thomsoni* (pleco or "corroncho") (INCODER, 2007). These fish are sought after in the aquarium trade due to their distinctive physical appearance, variable coloration, calm behavior, and their role as cleaner fish. Additionally, they are known for their high adaptability and tolerance to environments with elevated concentrations of nitrogen compounds, broad thermal adaptability, rapid growth, easy reproduction, and ease of handling (Favré, 1978).

Many species of the Loricariidae family are marketed as small fish. However, it is well known that the overall development of fish depends largely on environmental parameters such as water temperature and nutrition. Due to this characteristic, some species, like *C. fischeri* (Ortega-Lara et al., 2006), can reach sizes above 300 mm, and in some cases, they are released into the wild. This makes them introduced fish that can cause ecosystem imbalance due to their voracious behavior and high adaptability to various environments and thermal zones (Favré, 1978). Morphometric reports of *C. thomsoni* captured in the Porce River show sizes ranging from 33 mm to 219 mm (Jiménez-Segura et al., 2014), contrasting with smaller sizes observed in the present study (from 49.59 mm to 144.9 mm). This result may be related to the time of year when they were monitored, as the sampling points were the same. In the first description of *C. thomsoni*, three specimens with a length of 110 mm were captured in Villeta, Cundinamarca, Colombia (Regan, 1904). The genus *Chaetostoma* has shown maximum sizes of up to 300 mm in some species, such as *C. leucomelas* (Maldonado-Ocampo et al., 2005) and *C. fischeri* (Ortega-Lara et al., 2006).

Among the most important characteristics of the Loricariidae family are the adaptations of the oral apparatus, which features an oral sucker that may be present only on the lower lip, as in the case of *C. thomsoni* (Regan, 1904), or on both lips, as observed in *Hypostomus pyrinensi* (Dueñas, 2008). The family also exhibits teeth adapted for hard substrates depending on the genus and, additionally, one or two pairs of barbels located laterally on the upper lip (Favré, 1978). These adaptations enable the fish to adhere strongly to rocky substrates and scrape them in order to feed on algae or microorganisms present there.

It was observed that the number of odontodes does not depend solely on the age or size of the fish, as they are easily lost due to being made of dentin. Furthermore, odontodes were found in different sizes in both juveniles and adults, suggesting that they may regenerate, like scales, which are also composed of dentin in teleosts, according to a previous report (Sire & Huysseune 1996).

The cardiac puncture is mainly used when caudal vein puncture is not feasible due to the species' anatomical characteristics, such as in fish belonging to the Loricariidae family, which have their bodies covered by bony plates. To perform cardiac puncture, the fish is placed in a lateral or ventral position, and the needle is inserted into the cardiac ventricle from the lateral angle or ventral to the heart of the fish, with a slight vacuum applied to the syringe. In some species, it is also possible to collect blood by inserting the needle through the operculum from the base of the gills to the heart (Ranzani et al., 2013, Duman et al., 2018). However, in *C. thomsoni*, it is impossible to perform cardiac puncture through the operculum because this last part is separated from the cardiac cavity by bone plates. It is essential to highlight that performing a puncture in a vital organ such as the heart carries a greater risk to the fish's health than using blood vessels. This action could result in profuse hemorrhages that can lead to the fish’s death or cause areas of tissue damage and even myocardial necrosis (Ranzani et al., 2013).

The study of the digestive system in wild fish species is of paramount importance, as anatomical variations reflect differential ecological resource utilization. Fish from the Loricariidae family play a significant role in the energy recycling of neotropical aquatic ecosystems (Pessoa et al., 2013). Fish that consume fine-grain detritus possess rudimentary labial and pharyngeal teeth, thin stomach walls, and long intestines, as reported for the species *Rhinelepsis aspera* (Delariva & Agostino, 2001), which aligns with our findings for *C. thomsoni*. These authors also reported other species of the Loricariidae family that consume coarser food (periphyton); therefore, they have longer and stronger teeth, a more developed stomach, and a shorter intestine, such as *Megalancistrus aculeatus* and *Hypostomus microstomus*. There are also species with intermediate characteristics, such as *H. regani*, *H. ternetzi*, and *H. margaritifer* (Delariva & Agostino, 2001).

The stomach of Loricariidae exhibits similar characteristics among species. Several authors attribute respiratory functions to the stomach, in addition to digestive functions (Pessoa et al., 2013; Delariva & Agostino, 2001; de Oliveira et al., 2001; da Cruz et al., 2009). According to Armbruster (1998), Loricariid catfishes have evolved modifications of the digestive tract that function as accessory or hydrostatic organs, such as an enlarged, clear, air-filled stomach, and U-shaped or ring-like diverticula that are similar to swim bladders and may be used as hydrostatic organs (Armbruster, 1998). In some species, the ability to breathe air in the stomach has been confirmed (de Oliveira et al., 2001). For *Chaetostoma*, a slight ability to breathe air under hypoxia has been reported. The stomach is an excellent structure for breathing because of its connection with the outside of the body and its high vascularization (Armbruster, 1998). Given that the findings in *C. thomsoni* were similar to those reported previously, it is highly probable that this species has this dual function in the stomach, especially considering its lack of a swim bladder.

There are reports of the presence of quite long, spiral-shaped intestine in other species of the Loricariidae family, such as *Hypostomus pusarum* (Pessoa et al., 2013), *Rhinelepsis* aspera, *Megalancistrus aculeatus*, *Hypostomus microstomus*, *H. regani*, *H. ternetzi*, and *H. margaritifer* (Delariva & Agostino, 2001). This finding is similar to what was observed in the present study for *C. thomsoni*. A long intestine is in line with the type of algivorous and detritivorous feeding, which is abundant but difficult to digest and has low nutritional value (Pessoa et al., 2013; Delariva & Agostino, 2001).

For several species of loricariids, the presence of the liver in the center of the intestinal spiral has been reported (Pessoa et al., 2013; Delariva & Agostino, 2001). However, the histological evaluation conducted in the present study for *C. thomsoni* revealed that this structure is the hepatopancreas. Further histological studies in other loricariid species will be necessary to confirm if this is the case for other species as well.

Regarding the ovaries, the large size of the eggs found in some specimens of *C. thomsoni* is a remarkable characteristic also found in other species of Loricariids such as *Lithoxus*, with mature eggs measuring up to 2.2 mm, proportionally very large for the small size of the fish (41.4 mm) (Armbruster, 1998). *C. thomsoni* presents a synchronous development of multiple groups or an asynchronous development, the latter referring to species with more than one group of developing oocytes and is characteristic of species that spawn several times within the same spawning season (tropical fish) (Sierra-de la Rosa, 2007). In the present study, the maturation stage of oocytes was classified into three developmental stages: maturation phase one (< 1 mm); maturation phase two (1-2 mm); and mature stage three or pre-spawning (> 2 mm); similar to what was reported by other studies for this species, which reported a smaller minimum diameter of 0.6 mm, and the largest diameter in mature oocytes as 3.8 mm (Loaiza et al., 2018).

One of the most significant findings of the present study is the shape of the cranial kidney of *C. thomsoni*, which exhibits a bifurcated arrangement cranially, partially enveloping the brain. The cranial part of the kidneys, as identified in this study, was found to have hemolymphopoietic, endocrine, and immunological functions, consistent with the characteristics described for most fish (Plaul et al., 2012). However, the presence of this structure had not been previously described in fish of the Loricariidae family.

In general, the native ichthyofauna of the Porce River basin has been poorly described both morphologically and histologically. New knowledge about this species will allow for a better ecological understanding and improved management during monitoring efforts. Moreover, establishing a baseline in the study of internal organs, some of which were described here for the first time, will enable the recognition and determination of the health status of fish in future sampling. Hematological and hepatic findings, as well as the evaluation of gills, among other factors, contribute to the study of the health conditions of fish in various sampled environments, including reservoirs, rivers, and streams. This, in turn, facilitates future research on the adaptive processes of ichthyofauna to the changing conditions of altered environments. Furthermore, these studies provide tools for decision-making regarding the implementation of programs aimed at the conservation and proper management of ichthyofauna to mitigate negative impacts on biodiversity.

Declarations

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Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the work presented in this report.

Author Contributions

Julieth Ayala-Combariza: conceptualization, investigation, writing of the original draft, methodology, review and editing, formal analysis, software, visualization, data curation. Julián David Muñoz-Duque: methodology, investigation, formal analysis, writing of the original draft, software, visualization. Lynda Jhailu Tamayo-Arango: writing of the original draft, review and editing, formal analysis, validation, data curation. Jenny Jovana Chaparro-Gutiérrez: conceptualization, funding acquisition, project administration, supervision, validation, resources. Luz Natalia Franco-Montoya: conceptualization, investigation, writing of the original draft, methodology, review and editing, formal analysis, visualization, software, data curation.

Use of artificial intelligence (AI)

No AI or AI-assisted technologies were used during the preparation of this work.

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