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CMFRI Campus, P.B. No.1604, Ernakulam North P.O., Kochi - 682 018, Kerala, India
Tel: 0484 - 2394867. Fax: 0484 - 2394909. E-mail: mail@mbai.org.in; mbai@rediffmail.com **www.mbai.org.in**

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The Marine Biological Association of India
CMFRI Campus, P.B. No.1604, Ernakulam North P.O., Kochi - 682 018
Kerala, India Tel: 0484 - 2394867. Fax: 0484 -2394909.
E-mail: mail@mbai.org.in; mbai@rediffmail.com

Founding Address
The Marine Biological Association of India
C/o Mandapam Regional Centre of CMFRI, Marine Fisheries P. O, Mandapam
Camp, Ramanathapuram District, Tamil Nadu- 623 520

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Short Communications

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Morphological and molecular characterisation of eggs and larvae of dark sleeper goby, *Butis humeralis* (Valenciennes, 1837), collected from a tropical estuary

M. K. Shameena[1, 2], V. L. Sruthy[2], R. Ratheesh Kumar[1]*, K. A. Sajeela[1] and P. Kaladharan[1]
[1]ICAR-Central Marine Fisheries Research Institute, Kochi- 682 018, Kerala, India.
[2] Cochin University of Science and Technology, Kochi- 682 022, Kerala, India.

*Correspondence e-mail: rkcmfri@gmail.com
ORCiD: https://orcid.org/0000-0002-3954-1619

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Original Article

Abstract

Eggs of *Butis humeralis* (Valenciennes, 1837) were described for the first time from the west coast of India. A cluster of sparsely distributed eggs of *B. humeralis* was observed on a gritted glass panel submerged for biofouling studies in the Cochin estuary, Kerala. The egg mass covered an area of 62 cm^2 with an average abundance of 120 ± 30 eggs/cm^2. Molecular characterisation of the egg was performed to confirm species identification. The brownish-yellow, sticky, pyriform-shaped, transparent eggs of *B. humeralis* measured 0.41 ± 0.01 mm in diameter along the long axis and 0.36 ± 0.01 mm along the short axis. The newly hatched larvae of *B. humeralis* were slender and translucent with a total length of 1.01 ± 0.037 mm. The total length of the preflexion larvae was 2.08–2.12 mm. DNA barcoding using partial mitochondrial cytochrome oxidase subunit I gene sequences confirmed species identity, with 100% similarity to *B. humeralis* sequences from the Cochin estuary, which were deposited in GenBank. Genetic divergence analysis showed extremely low intraspecific variability (0.0%) and moderate interspecific divergence (5.7–24.7%), confirming genetic distinctness and clear taxonomic separation of *B. humeralis.* The first taxonomic description of the early life stages of this lesser-known species will facilitate future ichthyoplankton identification and contribute to assessing its conservation status within the ecosystem.

***Keywords:** Goby, Cochin estuary, eggs, larvae, DNA barcoding*

Introduction

Sleeper gobies, or dark sleeper or olive flathead-gudgeon, belong to the family Eleotridae under the Order Gobiiformes (Fricke *et al.,* 2025). Eleotridae is composed of three subfamilies: Butinae, Eleotrinae and Milyeringinae (Fricke *et al.,* 2025). Eleotrids are primarily found in tropical and sub-tropical brackish and freshwater zones of Asia, Africa, and Australia (Thacker, 2011). Molecular phylogenetic examination of Gobiiformes suggests elevating the subfamilies Eleotrinae and Butinae to the families Eleotridae and Butidae, respectively, as new rank classifications (Thacker, 2009; Abdulmalik-Labe and Quilang, 2024). It is also native to Hong Kong, Thailand, and Papua New Guinea and has been reported from India, Vietnam, Bangladesh, Malaysia and Singapore. The subfamily Butinae within the family Eleotridae comprises nine species across five genera: *Butis*, *Bostrychus*, *Odonteleotris*, *Ophiocara* and *Incara*. The genus, *Butis,* includes seven valid species, such as *B. amboinensis* (Bleeker, 1853), *B. butis* (Hamilton, 1822), *B. gymnopomus* (Bleeker, 1853), *B. humeralis* (Valenciennes, 1837), *B. koilomatodon* (Bleeker, 1849), *B. melanostigma* (Bleeker, 1849) and *B. prismatica* (Bleeker, 1849). However, only five species, namely *B. amboinensis*, *B. butis*, *B. gymnopomus*, *B. humeralis*, and *B. koilomatodon*, were reported from India (Nair and Dineshkumar, 2018; Venkateswarlu, 1967; Geevarghese, 1981). *B. amboinensis* were only reported from the east coast of India, while *B. humeralis, B. butis, B. koilomatodon,* and *B. gymnopomous* were found in the Veli, Korapuzha-Kuttiadi, Ashtamudi, Kodungalloor-Azhikode, and

Vembanad estuarine waters of Kerala, on the south-west coast of India (Geevarghese, 1981; Gopi, 2006; Raghunathan, 2007; Zeena and Beevi, 2011; Nandan *et al.,* 2012; Krishnaprasad *et al.,* 2025).

The present study is the first description of *B. humeralis* eggs and early life stages. The study also provides a detailed description of egg morphology, hatching and changes associated with the growth and development of *B. humeralis* larvae under laboratory conditions, as well as the molecular characterisation of *B. humeralis* eggs from the Cochin estuary, Kerala.

Material and methods

Study area and sampling method

To examine the biofouling impacts on aquaculture cages and jetties, gritted glass panels (150 mm × 150 mm × 2 mm) were suspended at a depth of 1-1.5 m at the cage site near Kalamukku Fishing Harbour (9.59′ 11.7″ N 76.14′ 43.7″ E) in Cochin estuary, Kerala (Fig. 1). Numerous eggs were found adhered to the glass panel upon retrieval after twenty days in monsoon season. The glass panels with the eggs were carefully detached from the cages and transported to the laboratory for further investigation. A working-party zooplankton net with a mesh size of 300 μm was used to collect zooplankton during the post-monsoon (November 2021 and January 2022). Later, glass panels were dipped into a tray filled with filtered estuarine water (0.2 μm) collected from the study area to observe egg hatching and development in the laboratory. The physicochemical characteristics of surface water samples collected from the panel-immersed site were measured according to standard procedures (APHA, 1998).

Microscopic examination of the egg samples

A cluster of eggs was observed on the gritted glass panels and in zooplankton samples. Measurements of 150 eggs were taken under the stereo microscope (Nikon SMZ25 – NIS Elements D 5.30.00). The area of attachment of eggs on a gritted glass panel was calculated by counting the total number of grits containing eggs, multiplying it by the area of a single grit, and averaging the number of eggs per grit. These eggs were carefully detached from the panel using a brush and kept in a 1000 ml glass jar containing estuarine water collected from the cage site. They were observed every 24 hours to study the early developmental stages of the egg samples. A total of 6 and 25 eggs were counted from the zooplankton samples in November 2021 and January 2022, respectively. The taxonomic identification of *B. humeralis* eggs was carried out using similar morphologically identified eggs from the same family, Eleotridae (Lindstrom, 1999; Maeda *et al.,* 2008). The volume of the yolk sac and oil globule of eggs and developing larvae was calculated (Bagarinao, 1986).

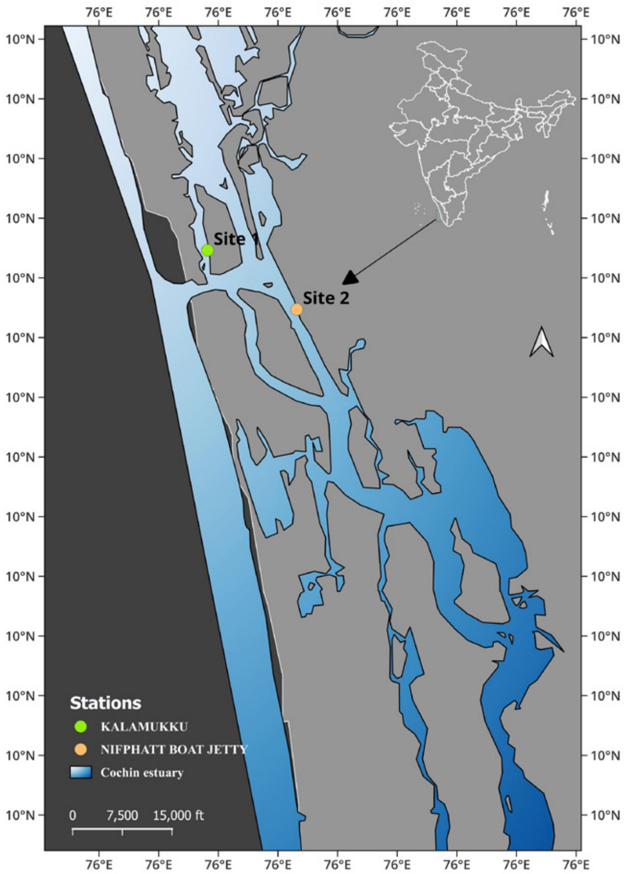

Fig. 1. Map showing the collection sites of *Butis humeralis* from Cochin estuary, Kerala, south-west coast of India

DNA barcoding of the egg samples

A subsample of the eggs collected and sorted both from the glass panel and total eggs from zooplankton samples was preserved in 95% ethanol. Total DNA was isolated using the DNeasy® Blood and Tissue kit (Qiagen, Germany), and its quality and quantity were assessed using the NanoDrop One Microvolume UV-Vis Spectrophotometer (Thermo Fisher Scientific). Molecular phylogenetic analyses were carried out using mitochondrial Cytochrome Oxidase I (COI) sequencing.

PCR carried out in 25 μl reactions using 2X EmaraldAmp GT PCR Master mix (Takara, Japan) using 20 pM of primers and 20 ng of template DNA (i.e., 12.5 μl of EmaraldAmp GT PCR Master mix, 0.25 μl primers (Fish F1 5′-TCAACCAACCACAAAGACATTGGCAC-3′ and Fish R1 5′-TAGACTTCTGGGTGGCCAAAGAATCA-3′) (Ward *et al.,* 2005) and 1 μl template DNA made up to final volume with nuclease-free water). The reaction mixture was preheated at 94 ^{0}C for 5 minutes, followed by 25 cycles (94 ^{0}C for 30 seconds, 50 ^{0}C for 30 seconds, and 72 ^{0}C for 35 seconds) and a final extension at 72 ^{0}C for 5 minutes. PCR products were visualised in a 1.5% agarose gel and compared with a NEX-GEN 100 bp DNA ladder (Genetix Biotech Asia Pvt. Ltd., New Delhi, India). PCR products were sent for sequencing to the sequencing facility at Enfys Lifesciences Pvt. Ltd. (Kerala, India). The forward and reverse DNA sequences were aligned and assembled using BioEdit sequence alignment editor, version 7.0.5.2 (Hall, 1999), and species-level morphological identifications were performed through sequence similarity searches using BLAST in GenBank.

Results

Observation of the gritted glass panel after 20 days of immersion showed that the egg mass covered an area of 61.80 cm^2 on the glass panel with an average of 120 ± 30 eggs/cm^2 (mean ± SD; n=10) and was irregularly distributed on the surface of the glass panel (Figs. 2a and b). The egg mass appeared to be a single clutch due to its homogenous growth and appearance. Owing to the sparse distribution, minute size of the eggs, and variability of the density within an egg mass, it was difficult to determine the accurate number of eggs within the clutch. Nevertheless, estimates of egg numbers from subsamples indicated that the clutch comprises 7,680 eggs / 61.80 cm^2. Morphologically similar eggs were also collected through seasonal zooplankton sampling from two different stations in the Cochin estuary during November 2021 and January 2022. The number of eggs per haul was 6 and 25, respectively (Fig. 3). The atmospheric temperature, water temperature, salinity, and pH of the study area during the retrieval of the gritted glass panels were 28 °C, 26 °C, 6 PSU, and 7.29, respectively. Other physicochemical parameters, such as turbidity, total suspended solids (TSS), and dissolved oxygen (DO), during the sampling period were 7.58 NTU, 28.67 mg L^{-1} and 5.43 mg L^{-1}, respectively. The nutrient concentrations, including inorganic nitrate, nitrite, inorganic phosphate, silicate, and ammonia, were 0.129 mg L^{-1}, 0.008 mg L^{-1}, 0.063 mg L^{-1}, 1.34 mg L^{-1}, and 0.03 mg L^{-1}, respectively.

Morphological characteristics of B. humeralis eggs

The egg mass appeared to be a single clutch due to its homogenous growth and appearance. Owing to the minute size and sparse distribution of the eggs and variability of the density within an

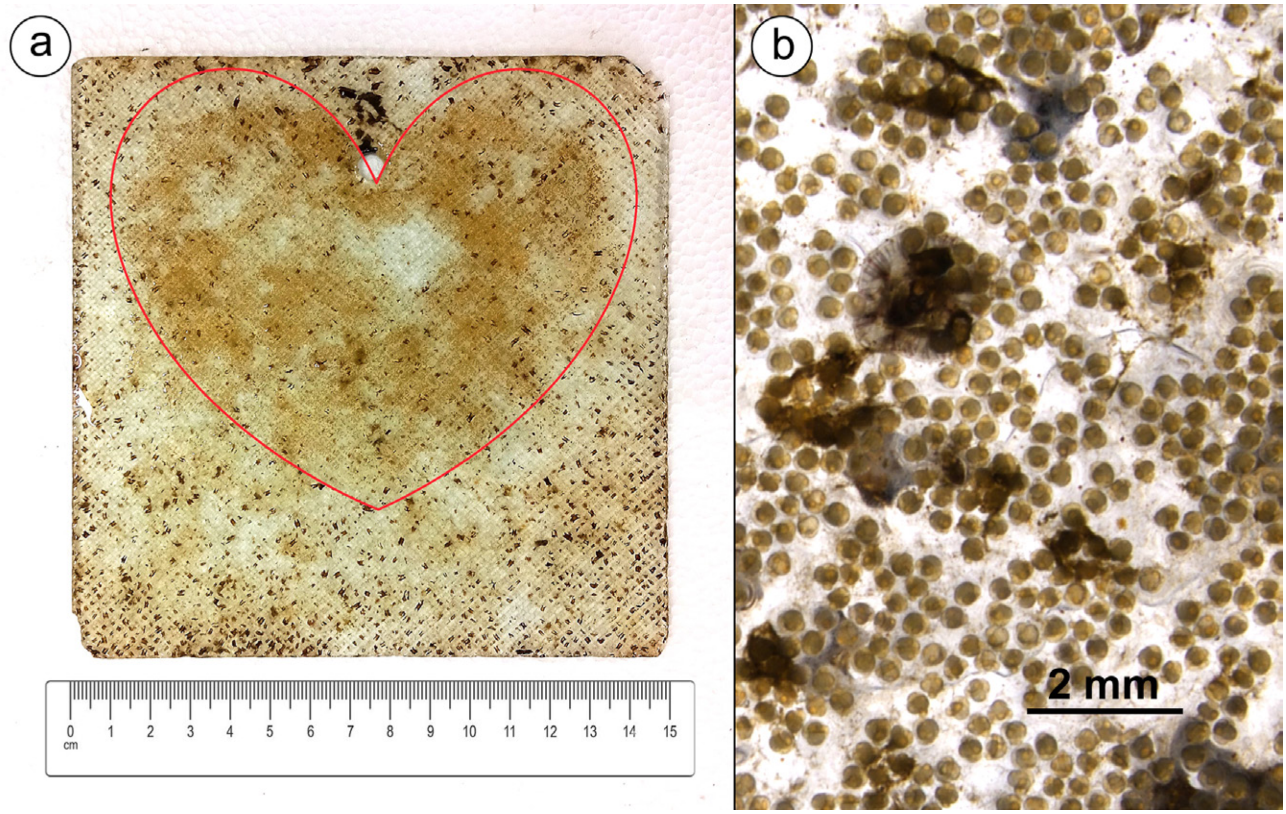

Fig. 2. a) Surface of the fouled gritted glass panel with egg mass of *B. humeralis* (shown within red heart shape area) after 20 days immersion near Kalamukku Fishing Harbour, Cochin Estuary, Kerala, b) Magnified picture of the centre of *B. humeralis* egg mass deposited on the surface of the gritted glass panel, showing the typical arrangement

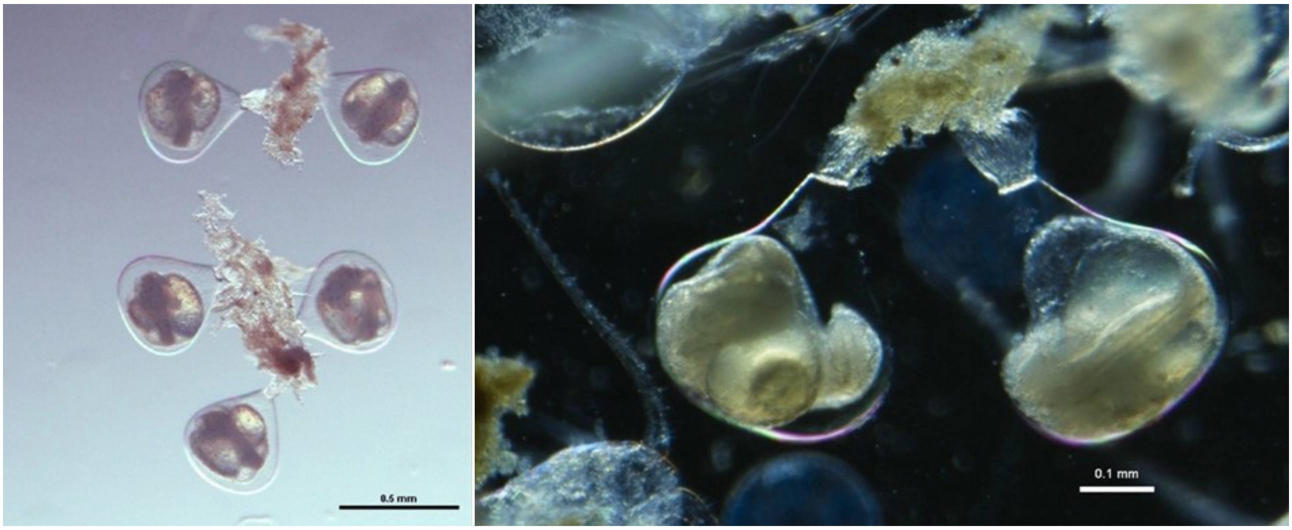

Fig. 3. Eggs of *B. humeralis* from zooplankton samples collected from NIFPHATT Jetty

egg mass, it was difficult to determine the accurate number of eggs within the clutch. The demersally attached eggs of *B. humeralis* attached to gritted glass panels were brownish in colour, pyriform in shape and measured 0.41 mm × 0.36 mm (Fig. 4a). The perivitelline space was very narrow, with the embryo occupying almost the entire vitelline space. The pointed end of the egg comprised a bundle of adhesive filaments that held the neighbouring eggs together on the surface in a monolayer. The yolk was clear, unsegmented, and golden in colour, with 4-6 oil globules present 5 min before hatching at the embryonic stage. The chorion appeared clear and smooth under stereomicroscopic observation. The eggs showed twitching and heartbeat movements during the late segmentation or pre-hatching stage. The egg possessed a primitive optic vesicle, notochord, and yolk sac containing numerous oil globules, each measuring 0.076 ± 0.03 mm in diameter. Shortly before hatching, numerous tiny oil droplets coalesced into two globules. Twitching and wriggling movements became more vigorous just before hatching. The embryo ruptured the egg capsule, and the yolk sac larva came out within 2 to 3 hours after being brought to the laboratory (Fig. 4b). *B. humeralis* larvae were poorly developed at the time of hatching and lacked a functional mouth, smaller size of eggs with narrow perivitelline space and yolk diameters less than 1 mm. Volume of yolk sac and oil globule reduced with larval development (Table 2).

DNA barcoding of B. humeralis eggs

The three aligned sequences used for similarity search (BLAST) in the NCBI database showed 100% identity and query coverage to *B. humeralis.* The generated sequence was submitted to the NCBI

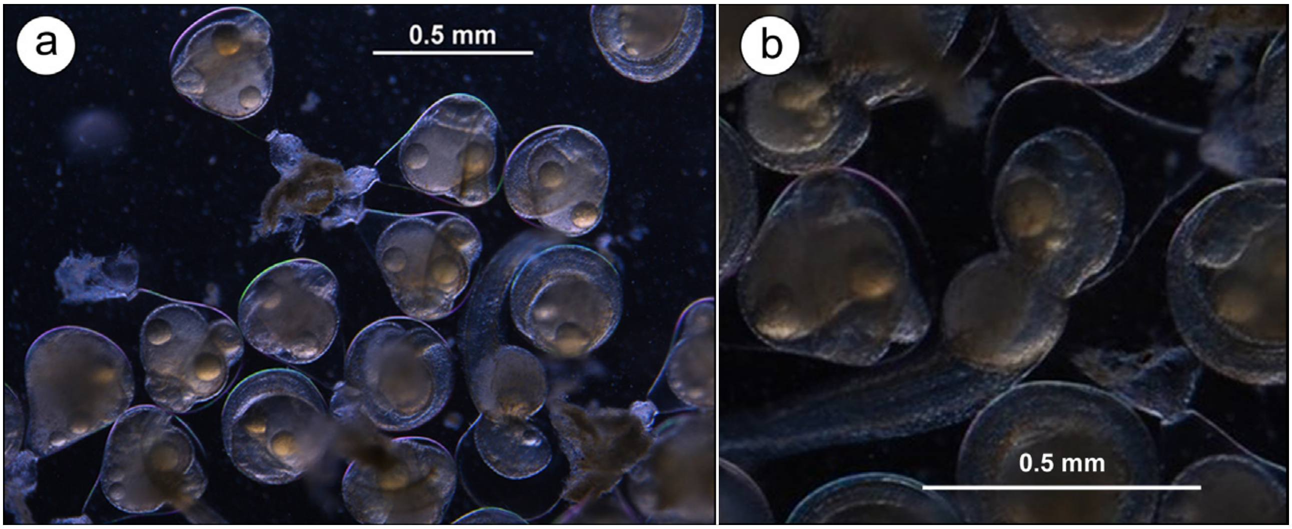

Fig. 4. a) Eggs of *B. humeralis* in the twitching and heart beating stage showing the orientation of embryos within the chorionic cavity. Adhesive filaments at the pointed end adhered the eggs to the surface of the spawning site, b) Yolk sac larval hatching of *B. humeralis* by penetrating through the egg membrane

GenBank with Accession Nos. OP872738, PZ256944, PZ256945. The genetic divergence values estimated using MEGA X among similar species of *Butis* (Table 3). The neighbour-joining (NJ) tree generated using the Kimura 2-parameter model showed three major distinct clades with high bootstrap support values. *O. marmorata* (PP085180) has been taken as an outgroup to root the tree (Fig. 6). The *B. humeralis* sequences (MK359460, MK359458, OP872738) formed a monophyletic cluster with 100% bootstrap support, indicating very low genetic divergence. Other *Butis* sequences subgroups (PZ256944, PZ256945) within the *Butis humeralis* cluster formed moderate to high bootstrap support values. The genetic differentiation from related species (*B. koilomatodon*, *B. butis*, *B. amboinensis*) within the family is also evident in the phylogeny. The outgroup *O. marmorata* confirmed the appropriate rooting of the phylogenetic tree. Pairwise genetic analysis using the Kimura 2-Parameter (K2P) revealed clear patterns of divergence within and between *Butis* species. Intraspecific distances were extremely low (0.000 to 0.008), showing minimal genetic variability. However, interspecific distances were higher (0.054 to 0.178), indicating strong divergence among most *Butis* species.

Systematics

Order: Gobiiformes (Günther, 1880)
Family: Eleotridae (Bonaparte, 1835)
Subfamily: Butinae (Bleeker, 1874)
Genus: *Butis* (Bleeker, 1856)
Species: *Butis humeralis* (Valenciennes, 1837)
Larval development of B. humeralis

The larval development of *B. humeralis* in the laboratory, with relation to the time period after hatching and characteristic features of each stage, is shown. (Table 1 and 2 and Figs. 5 a-g). Progressive morphological and behavioural changes in larval development occurred from egg hatching to 144 hours post-hatch (HPH). At hatching of eggs (0 HPH), the released yolk sac (0.55–0.62 mm) larvae were (0.97–1.09 mm notochord length (NL)) translucent, with initial pigmentation and oil globules visible. By 24 HPH, partial yolk absorption, embryo fin fold formation and 'swim-up and sink' movements were exhibited. At 48 HPH preflexion larvae (1.53–1.55 mm NL) showed prominent head development, full absorption

Table 2. Volume of yolk sac and oil globule from 0 to 96 HPH

After hatching (hours)	Volume of yolk sac ($V = \pi/6\ l\ h^2$) (mm^3)	Volume of oil globule ($V = \pi/6\ d^3$) (mm^3)
	Bagarinao (1986)	Bagarinao (1986)
0	0.05239 ± 0.01039	0.00026 ± 0.00024
24	0.00835 ± 0.00119	0.00015 ± 0.00008
48	0.00154 ± 0.00013	Completely absorbed
72	0.00034 ± 0.0000	Absent
96	Yolk exhausted	Absent

Table 1. Larval development of *B. humeralis* in the laboratory

Day	Hour Post-Hatch (HPH)	Length (mm)	Characteristics
1	0	0.97-1.09 NL 0.99-1.11 TL	Yolk sac larvae (Fig. 6a) were slender and translucent, having a large, slightly oval, brownish coloured yolk sac. Numerous oil globules coalesced into two in the yolk sac. Primitive optic vesicles and otoliths formed laterally on the head. Pigmentation appeared on the tip of the snout, above the eyes, on the anterior and posterior margins of the yolk sac, ventrally on the posterior half of the trunk, ventrally on the anterior two-thirds of the tail, and dorsally on the midtail.
2	24	1.15-1.2 NL 1.19-1.25 TL	The yolk sac was partially reduced in diameter. The embryonic fin fold formed. Myomeres were partially visible. Melanophores and xanthophores above the eyes disappeared, and portions of the eye margin turned pigmented. Ventral melanophores and xanthophores were reduced on the anterior margins of the yolk sac, and irregular bands of pigments appeared on its trunk and caudal region. The larvae exhibited slight movements using "swim up, sink" behaviour with their tail (Fig. 6b).
3	48	1.53-1.55 NL 1.55-1.57 TL	The head and unopened mouth appeared as a prominence or bump. The yolk sac was further reduced in diameter. Oil globules were completely absorbed. Lens and choroid fissures were formed on the eye located at the anterior-lateral position of the head. The Notochord became distinct. Myomeres were well-developed, with 15 pre-anal and 45 post-anal myomeres. Anus and pectoral fin bud were slightly visible. Melanophores appeared above the eye, yolk sac and head. Vertical melanophore bands prominently appeared on the body and caudal region. Larvae started swimming with constant tail movements (Fig. 6c).
4	72	1.53-1.55 NL 1.55-1.57 TL	Remnants of the yolk sac were apparent. The mouth cleft was prominent. The eyes became dark and fully pigmented. Pectoral fins developed (Fig. 6d).
5	96	1.54-1.56 NL 1.56-1.58 TL	Well-developed mouth formed with clearly distinct upper and lower jaws. The yolk sac was completely absorbed. Larvae displayed wandering movements with frequent opening of the upper and lower jaws. Melanophores were observed in series along the lower jaw, below the gut, and on the dorsal and ventral lines of the body. Dorsal, anal, and caudal fin folds were also present (Fig. 6e).
6	120	1.6-1.7 NL 1.67-1.69 TL	Mouth opened with a gap of 0.04–0.05 mm. Body depth at the anus was 0.25 – 0.26 mm. Pectoral fin length was 0.12 – 0.14 mm. Head length and head depth were 0.28 – 0.29 mm and 0.26 – 0.27 mm, respectively. Eye diameter was 0.12 – 0.13 mm (Fig. 6f).
7	144	1.96-2.0 NL 2.08-2.12 TL	The growth of the upper and lower jaw slowed compared to the previous days. The head length slightly increased (Fig. 6g). The pectoral fin is well developed, and the larva began stable swimming.

NL denotes Notochordal Length; TL denotes Total Length

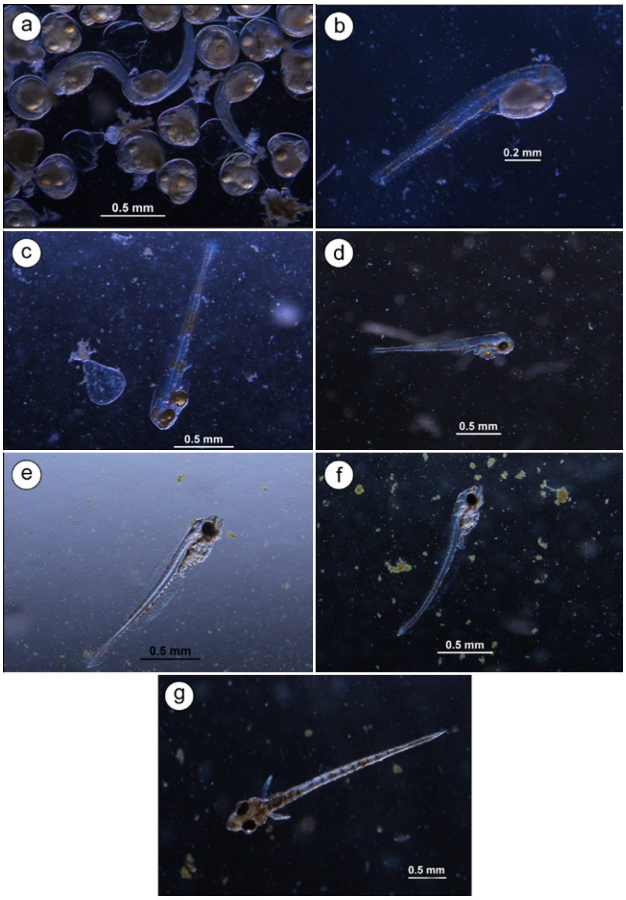

Fig. 5. Larval development of *B. humeralis* a) 0 HPH, b) 24 HPH, c) 48 HPH, d) 72 HPH, e) 96 HPH, f) 120 HPH, g) 144 HPH (dorsal view)

of the oil globule, a peculiar notochord, and well-developed myomeres. At 72 HPH, the yolk sac is nearly absorbed, the eyes are pigmented, and the pectoral fins are developed. At 96 HPH, yolk absorption is completed with active body movement; at 120 HPH (1.6–1.7 mm NL), mouth opening occurs. Eye diameter and body depth were clearly defined. At 144 HPH, larvae (1.96–2.12 mm) showed growth improvement, pectoral fin development and stable swimming behaviour (Table 1 and 2).

Discussion

B. humeralis is classified under the IUCN as Least Concern (LC). It was reported from the Indian Sundarbans and the Digha coast in West Bengal (Chatterjee *et al.,* 2013; Mishra and Gopi, 2017; Yennawar *et al.,* 2015), and from the coastal and estuarine waters of Tamil Nadu (Jeyaseelen and Krishnamurthy, 1981). The current study confirms the presence of *B. humeralis* in the waters of Kerala and provides the first description of its early developmental stages.

B. humeralis shares similarities in egg morphology with those of the two sleeper gobies of family Eleotridae, *Eleotris fusca* and *Eleotris acanthopoma*, as well as with *Lenticeps concolor* (indigenous Hawaiian goby) and *Stiphodon percnopterygionus* (sicydiine goby). The eggs of these gobies are pyriform and adhere to the substrate with a bundle of adhesive filaments. (Lindstrom, 1999; Maeda *et al.,* 2008; Yamasaki and Tachihara, 2006). Therefore, this study shows limitations in morpho-taxonomic identification due to the lack of standard literature. The *B. humeralis* sequence developed for this study showed 100% similarity and query coverage to the two sequences (Accession numbers: MK359460, MK359458), which were previously deposited from the Cochin estuary. DNA barcoding provides higher accuracy (94-99%) than the visual identification of fish eggs. (Mateos-Rivera *et al.,* 2020). Limitations of morphological taxonomy are overcome by molecular identification using COI genes (Hou *et al.,* 2022). DNA metabarcoding is a faster and more cost-effective method than individual barcoding, but individual barcoding yields better results (Breitbart *et al.,* 2023). Hence, DNA barcoding and molecular characterisation enabled more accurate species identification.

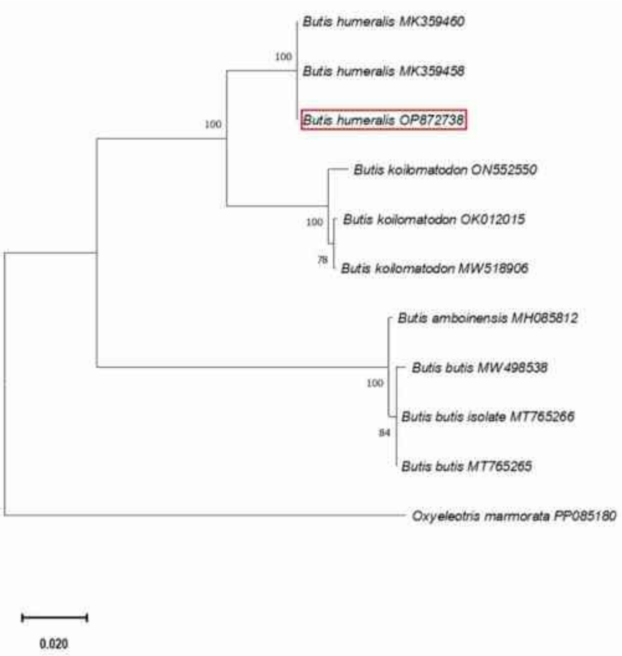

Fig. 6. Neighbour-Joining (NJ) Tree of COI sequences from four species of *Butis*. The sequence of *Oxyeleotris marmorata* was used as the outgroup. Accession number from the study

Although information on the early developmental stages of *B. humeralis* is currently lacking, the present study is relevant, as it details egg morphology, hatching, and the development of the preflexion larva up to 144 HPH by monitoring changes in eyes, pigmentation, fins, yolk sac size, oil globules, and mouth. Although identifying the early life stages of fish is challenging due to rapid developmental changes, DNA barcoding using

Table 3. Pairwise genetic distances between *Butis* species using the K2P model

	OP872738 *B. humeralis*	MK359458 *B. humeralis*	MK359460 *B. humeralis*	PZ256944 *B. humeralis*	PZ256945 *B. humeralis*	OK012015 *B. koilomatodon*	ON552550 *B. koilomatodon*	MW518906 *B. koilomatodon*	MT765265 *B. butis*	MT765266 *B. butis*	MW498538 *B. butis*	MH085812 *B. amboinensis*	PP085180 *O. marmorata*
OP872738 *B. humeralis*	****												
MK359458 *B. humeralis*	0.000	****											
MK359460 *B. humeralis*	0.000	0.000	****										
PZ256944 *B. humeralis*	0.000	0.000	0.000	****									
PZ256945 *B. humeralis*	0.000	0.000	0.000	0.000	****								
OK012015 *B. koilomatodon*	0.056	0.056	0.056	0.054	0.058	****							
ON552550 *B. koilomatodon*	0.061	0.061	0.061	0.060	0.064	0.008	****						
MW518906 *B. koilomatodon*	0.056	0.056	0.056	0.054	0.058	0.000	0.008	****					
MT765265 *B. butis*	0.160	0.160	0.160	0.144	0.142	0.169	0.174	0.169	****				
MT765266 *B. butis*	0.160	0.160	0.160	0.144	0.142	0.169	0.174	0.169	0.000	****			
MW498538 *B. butis*	0.164	0.164	0.164	0.144	0.142	0.173	0.178	0.173	0.003	0.003	****		
MH085812 *B. amboinensis*	0.157	0.157	0.157	0.144	0.142	0.166	0.171	0.166	0.003	0.003	0.007	****	
PP085180 *O. marmorata*	0.214	0.214	0.214	0.225	0.221	0.228	0.232	0.228	0.246	0.246	0.243	0.246	****

the COI gene improves taxonomic identification, supported by robust reference databases (Jiang *et al.,* 2024; Sruthy *et al.,* 2025). Many gobies hatch after eye pigmentation (Shinomiya *et al.,* 1981 a, b; Suzuki *et al.,* 1988; Suzuki *et al.,* 1989). However, eye pigmentation in *B. humeralis* started slightly at 24-hour post-hatch (HPH) and became densely pigmented at 72 HPH. The yolk sac stage begins at hatching and ends with yolk absorption (Kendall, 1984). In the present study, the absorption times of the yolk and oil globules were observed at 96 HPH, the same as in *Dormitator latrifrons* of the same family Eleotridae (Reyes-Mero *et al.,* 2022). During yolk and oil globule exhaustion, the larvae of *B. humeralis* developed pigmented eyes and differentiated fins, enabling them to survive progressive starvation as they transitioned from endogenous to exogenous feeding.

Gobies lay pear or pyriform-shaped eggs in demersal habitats, where they attach to surfaces in single layers (Russell, 1976). The egg masses of *Stiphodon percnopterygionus* (sicydiine goby) were guarded by the male and laid on the undersides of stones in freshwater (Yamasaki and Tachihara, 2006). Most gobiids exhibit an iteroparous reproductive pattern, in which females deposit eggs on vegetation or substrates, while males provide post-fertilisation parental care (Trujillo-García *et al.,* 2024).

According to Koumans (1953) and Miller *et al.* (1989), the habitat of *B. humeralis* ranges from marine to freshwater environments. Hui *et al.* (2010) reported that *B. humeralis* may survive in freshwater but may not breed successfully if access to the marine environment is restricted. In the present study, the *B. humeralis* eggs were found in an estuarine environment with a salinity of only 6 PSU at the time of collection. Although the two stations in the Cochin estuary have a direct connection to the sea through Cochin Barmouth, freshwater-seawater interactions occur regularly due to river water discharge and tidal forces. Therefore, the present scenario supports the previous investigations. The lunar cycle is crucial for their spawning and larval recruitment in estuaries (Miller, 1984; Thresher, 1984; Berra, 2001; Dinh *et al.,* 2016). In this study, the mature eggs of *B. humeralis* were collected five days before the new moon from Cochin Estuary. Here, hatching may also coincide with the lunar cycle, as it does in the wild.

The COI-based genetic distance analysis and the phylogeny of *B. humeralis* validate the genetic distinctiveness of most *Butis* species and reveal typical interspecific divergence consistent with species-level separation.

Conclusion

This study is the first taxonomic description of *B. humeralis* eggs and early life stages on the west coast of India, detailing egg morphology, early larval development, and molecular characterisation. *B. humeralis* eggs were demersal, pyriform, and surface-attached with filaments forming a single clutch, which probably indicates external fertilisation and the typical parental care strategy of Gobiids. Results emphasise both the limitations of accurately identifying morphologically similar gobiid eggs and the taxonomic resolution provided by DNA barcoding. Progressive morphological changes occur in larval stages from egg hatching to 144 HPH, and at 96 HPH, yolk absorption is completed. Cochin estuary, part of the Vembanad-Kol Wetland, one of Kerala's three Ramsar sites, is the largest estuary along the southwest coast of India. The presence of substratum-attached *B. humeralis* eggs and their occurrence in zooplankton samples from Cochin estuary indicate that this estuary provides ideal conditions for the breeding and nursing of this species. This study enhances understanding of the early life history of *B. humeralis* and the use of DNA barcoding to identify ambiguous and unknown ichthyoplankton.

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Author contributions

Conceptualisation: SMK, VLS; Methodology: MKS, VLS, KAS; Data Collection: SMK, VLS; Data Analysis: SMK, VLS, RRK; Writing Original Draft: VLS, SMK; Writing Review and Editing: RRK, PK; Supervision: RRK, PK

Data availability

The data are available and can be requested from the corresponding author. The generated sequence was submitted to NCBI GenBank with Accession Nos. OP872738, PZ256944, PZ256945.

Conflicts of interest

The authors declare that they have no financial or non-financial conflicts of interest that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval was required as the study did not involve activities requiring ethical clearance or the use of protected organisms/ human subjects/ collection of sensitive samples/ protected environments.

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Publisher's note

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Phytoplankton distribution in pre-monsoon and post-monsoon seasons and its relation with physicochemical parameters in coastal waters of Ratnagiri, West Coast of India

Prathamesh J. Ade[1]*, Aniruddha D. Adsul[1], Rajiv H. Rathod[2], Sachin W. Belsare[2], Sagar A. Joshi[2], Pratiksha V. Nimbarte[1] and Mayuresh S. Nagawekar[1]

[1]College of Fisheries, Ratnagiri, Dr Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli-415629, Maharashtra, India.

[2] College of Fishery Science, Nagpur, Maharashtra Animal and Fishery Sciences University, Nagpur-440006, Maharashtra, India.

*Correspondence e-mail: praveshade7@gmail.com
ORCiD: https://orcid.org/0009-0007-2045-8253

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Abstract

The present study evaluated phytoplankton assemblages and their interaction with physicochemical parameters along the coastal waters of Ratnagiri, Maharashtra, West Coast of India. Water temperature, pH, dissolved oxygen, alkalinity, nitrite, nitrate, ammonia, silicate, phosphate, and Chl-a were measured at four sampling stations. A total of 26 diatom species and 6 dinoflagellate species were recorded, with *Skeletonema costatum* and *Thalassionema frauenfeldii* having the highest abundances. Canonical Correspondence Analysis (CCA) identified alkalinity and silicate as the key factors driving phytoplankton dispersion and seasonal variations, whereas other nutrients had lesser effects. Diatoms regularly dominated over dinoflagellates throughout the pre- and post-monsoon seasons. Overall, alkalinity and silicate appeared as the key drivers of phytoplankton community structure, while diversity indices revealed probable anthropogenic influence at a few sampling locations.

Keywords: *Phytoplankton, diversity index, CCA, Maharashtra*

Introduction

Coastal zones are among the most ecologically productive and economically valuable regions on Earth, encompassing habitats such as coral reefs, mangroves, estuaries, and seagrass beds. These systems support a wide array of ecosystem services and human activities, including fisheries, aquaculture, tourism, and transportation, that are critical to coastal livelihoods and food security. However, the increasing intensity of anthropogenic activities, coupled with the impacts of climate change, has significantly reduced the resilience of coastal ecosystems, making them more vulnerable to environmental degradation (Bijlsma *et al.,* 1996). The ecological dynamics of coastal systems are influenced by both natural processes and human interventions. Factors such as water exchange with adjacent marine areas, coastline morphology, precipitation, and riverine input create unique hydrological and physicochemical conditions in each region (Ilyash *et al.,* 2015). These environmental gradients strongly influence the distribution, abundance, and succession of phytoplankton communities, key primary producers that form the base of the aquatic food web (Biswas *et al.,* 2015). Phytoplankton play a crucial role in supporting aquatic food chains by serving as a direct food source for zooplankton, shellfish, and finfish (Price, 2001). Owing to their sensitivity to environmental changes such as temperature, light, salinity, and nutrient availability, they are widely used as biological indicators of water quality and ecosystem health (Gharib *et al.,* 2011). Seasonal and spatial variability in these parameters often results in distinct phytoplankton community structures, making them effective tools for monitoring aquatic ecosystems.

In India, extensive research has been conducted on phytoplankton dynamics across various coastal and estuarine systems along the west coast, including the Cochin backwaters (Madhu *et al.,* 2007, 2010), the Mandovi-Zuari estuary (Patil and Anil, 2011, 2015) and Mumbai coastal waters (Ramaiah *et al.,* 1998; Jaiswar *et al.,* 2013). These studies have emphasised the influence of monsoon, eutrophication, and physicochemical parameters on phytoplankton assemblages. It is well documented that estuaries and nearshore coastal zones are biodiversity hotspots serving as nurseries for commercially important fish species (Kawabata *et al.,* 1993; Saravanakumar *et al.,* 2008), and the phytoplankton communities within these habitats are therefore vital to maintaining ecological balance and productivity. Despite this growing body of research along India's west coast, however, limited data are available on phytoplankton community dynamics specific to the Jiagad, Ratnagiri coastal area is a less-studied but ecologically important region. Thus, understanding the phytoplankton distribution and their relationship with environmental variables in this area is essential for assessing the ecological status and guiding sustainable coastal management. In light of these considerations, the present study aims to investigate the species composition and community structure of phytoplankton in the Jiagad coastal waters in relation to key water quality parameters in the post-monsoon and pre-monsoon seasons. The findings will provide insights into the spatial and temporal variations in phytoplankton assemblages and enhance our understanding of their role as bio-indicators in a changing coastal environment.

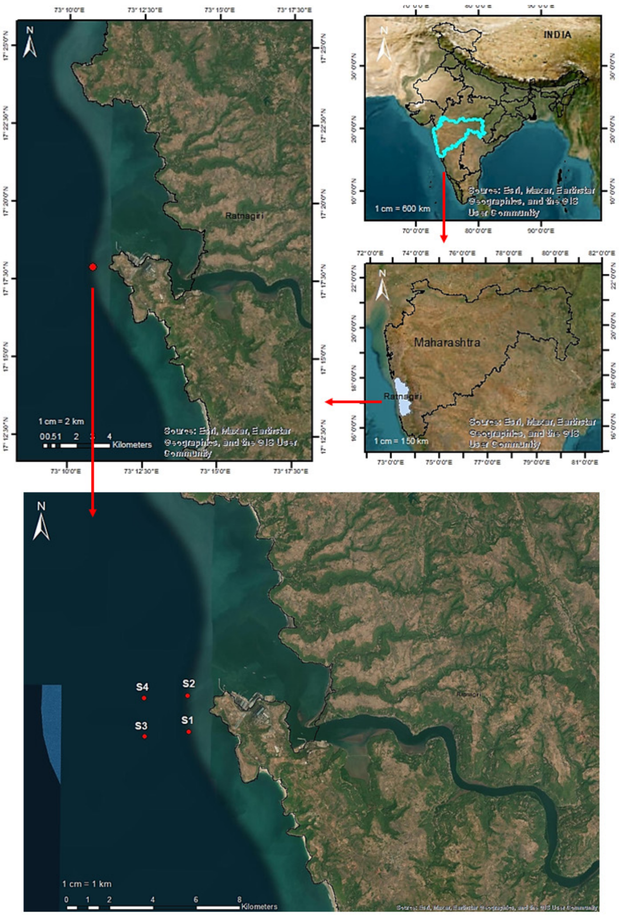


Fig. 1. Sampling stations along the coastal waters of Ratnagiri

Material and methods

The present study was carried out at four sampling stations (S1, S2, S3 and S4) twice a month along the Jaigad coastal area from October 2023 to May 2024 (in pre-monsoon and post-monsoon seasons, excluding the monsoon season) for a total time period of eight months (Fig. 1). Sampling was carried out at four designated stations where station S1 and S2 were fixed at a depth of 18 m, while station S3 and S4 were located further offshore at a depth of 36 m. During each sampling, water samples were collected at each station for analysis of sea surface temperature, water pH, dissolved oxygen, salinity, nitrate, nitrite, reactive silicate, inorganic phosphate and Chlorophyll-a. Sea surface temperature was measured with a mercury thermometer, water pH with a digital pH pen (Eco Tester pH 2) with an accuracy of ±0.01 pH units, dissolved oxygen was estimated by Winker's method (Strickland and Parsons, 1972), water transparency was measured with a Secchi disk, salinity was estimated by using the argentometric method (Strickland and Parsons, 1972), and nutrients such as nitrite, nitrate, inorganic phosphate and silicate were estimated by the colorimetric method using standard procedures (Strickland and Parsons, 1972). A standard plankton net of diameter 0.25 m (Ø: 60 μm) was used for the plankton collection. For phytoplankton analysis, 50 L of the water sample was filtered through a plankton net with a 60 μm mesh size, and the sample was concentrated to a final volume of 200 mL (Jagadeeshappa and Kumara, 2013). Lugol solution and 5% neutralized formalin solution were used to preserve plankton samples. 1 ml of the concentrated sample was placed on the Sedgwick Rafter Chamber for taxonomic identification, and enumeration was done using a binocular microscope (ZEISS PrimoStar Binocular Microscope, 40X magnification). Identification of phytoplankton was done using the conventional taxonomic keys (Desikachary, 1959; Newell and Newell, 1977). The number of phytoplankton cells present in all 1000 grids was counted, and phytoplankton density (cells L^{-1}) was determined. Chlorophyll-a (Chl-a) concentration was analysed with the acetone extraction method Grasshoff *et al.,* 1999) for which water samples were collected at fixed stations in 250 ml plastic bottles and subsequently filtered through glass fibre filter paper with a pore size of 0.45 μm. Clean plastic bottles containing inorganic dissolved nutrients, such as silicate (SiO_4), ammonia (NH_4), phosphate (PO_4), nitrite (NO_2), and nitrate (NO_3), were gathered and stored in an icebox. In the laboratory, these water samples were filtered through Millipore filter paper (0.45 μm) and examined by the spectrophotometric technique and analysed using the standard procedures prescribed by APHA (2023). Pearson's correlation matrix (r), the Shannon-Wiener diversity index (H′ $\log_2$), Pielou evenness (J′), and canonical correspondence analysis (CCA) were used to determine the diversity and environmental drivers of phytoplankton assemblages, while CCA was mostly used to explore the environmental variables influencing the phytoplankton community. Phytoplankton species diversity index (H′) and evenness (J′) were calculated using PAST (v.4.0) according to species diversity (H′) = $\sum$ (Pi log2 (Pi)) (Shannon, 1963), and species evenness (J′) = H′/log2 (S) (Pielou, 1975). Where Pi = ni/n (proportion of the sample belonging to the ith species 'S' is the number of species). All the statistical analyses were performed using PAST (v 4.0) and OriginPro (v 9.8).

Results

All the physicochemical parameter results are represented in Table 1. The maximum mean SST (29.38 ^{0}C) was observed in the pre-monsoon season, while the minimum temperature (28.38 ^{0}C) was recorded in the post-monsoon season. Water pH was recorded as the highest (8.21) in the pre-monsoon season, while the lowest pH (8.09) was recorded in the post-monsoon season. Dissolved oxygen ranged from 3.80 to 5.25 mg L^{-1} in the entire sampling time. Salinity readings didn't vary significantly and varied between 32.18 psu and 33.25 psu. Nitrite concentration was measured at its lowest (0.01 μmol L^{-1}) in the pre-monsoon season and 0.02 μmol L^{-1} in the post-monsoon season. Nitrate values varied from 0.02 to 0.12 μmol L^{-1}, with high amounts recorded in the post-monsoon season. The maximum inorganic phosphate (0.19 μmol L^{-1}) was recorded in the late pre-monsoon season, while the lowest (0.014 μmol L^{-1}) was recorded in the post-monsoon season. The silicate content ranged from 0.23 μmol L^{-1} to 0.45 μmol L^{-1} in the total sampling period, with the greatest concentration in the pre-monsoon season (Fig. 2).

All four sampling stations (S1, S2, S3 and S4) were chosen for performing canonical correspondence analysis (CCA) to determine the relation between physicochemical parameters and phytoplankton abundance (Fig. 3, Table 2). Physicochemical parameters such as DO, phosphate, pH, water temperature and Chl-a appear to have a strong influence on phytoplankton distribution. Species such as *Ditylum brightwellii, Ditylum sol, Guinardia striata* and *Skeletonema costatum* appear on the negative side of axis 1, indicating that these species prefer lower water temperature, salinity and nitrate and nitrite concentration. *Thalassionema nitzschioides* indicates a positive association with higher values of water temperature and salinity. Axis 2 is associated with physicochemical parameters such as silicate, Chl-a, pH, dissolved oxygen and phosphate, and species such as *Ceratium breve, planktoniella sol, Ornithocercus* sp. and *Leptocylindrus danicus* are found near the centre of the plot, suggesting more tolerance to physicochemical parameters, while other species such

Table 1. Water quality parameters along the Jaigad coastal waters in the pre-monsoon and post-monsoon seasons

Seasons and stations	Parameters										
	Water Temperature (^{0}C)	pH	Alkalinity (mgL^{-1})	Salinity (psu)	DO (mgL^{-1})	NO_2 (μmol L^{-1})	NO_3 (μmol L^{-1})	NH_4 (μmol L^{-1})	PO_4 (μmol L^{-1})	SiO_4 (μmol L^{-1})	Chl-a (μmol L^{-1})
Pre-monsoon											
S_1	29.00 (±1.68)	8.16 (±0.05)	107 (±2.58)	32.88 (±0.63)	5.25 (±1.15)	0.01	0.02 (±0.02)	0.12 (±0.01)	0.19 (±0.10)	0.45 (±0.18)	0.86 (±0.18)
S_2	29.00 (±1.68)	8.21 (±0.07)	109.50 (±4.43)	33.00 (±0.41)	5.10 (±0.96)	0.01	0.05 (±0.03)	0.12 (±0.01)	0.18 (±0.05)	0.41 (±0.19)	0.74 (±0.16)
S_3	29.13 (±1.25)	8.15 (±0.07)	103.50 (±1.91)	33.00 (±0.41)	4.90 (±1.09)	0.02	0.06 (±0.01)	0.13 (±0.02)	0.18 (±0.07)	0.41 (±0.16)	0.51 (±0.12)
S_4	29.38 (±1.44)	8.14 (±0.04)	101 (±1.15)	33.25 (±0.65)	4.50 (±1.23)	0.01	0.08 (±0.02)	0.12 (±0.01)	0.14 (±0.04)	0.33 (±0.16)	0.45 (±0.14)
Post-monsoon											
S_1	28.38 (±1.03)	8.12 (±0.06)	106.50 (±1.00)	32.00 (±0.82)	4.35 (±0.85)	0.01	0.10 (±0.06)	0.014 (±0.02)	0.16 (±0.04)	0.38 (±0.11)	0.71 (±0.16)
S_2	28.38 (±1.03)	8.12 (±0.06)	103 (±4.76)	32.18 (±0.96)	4.45 (±1.15)	0.02 (±0.01)	0.10 (±0.02)	0.13 (±0.02)	0.16 (±0.03)	0.37 (±0.09)	0.57 (±0.14)
S_3	28.50 (±1.08)	8.11 (±0.03)	103.50 (±4.73)	32.50 (±0.82)	4.20 (±0.91)	0.02 (±0.01)	0.12	0.13 (±0.03)	0.15 (±0.01)	0.28 (±0.13)	0.62 (±0.14)
S_4	28.88 (±1.11)	8.09 (±0.07)	102.50 (±2.52)	32.50 (±0.82)	3.80 (±0.37)	0.01	0.12 (±0.01)	0.14 (±0.05)	0.13	0.23 (±0.07)	0.49 (±0.14)

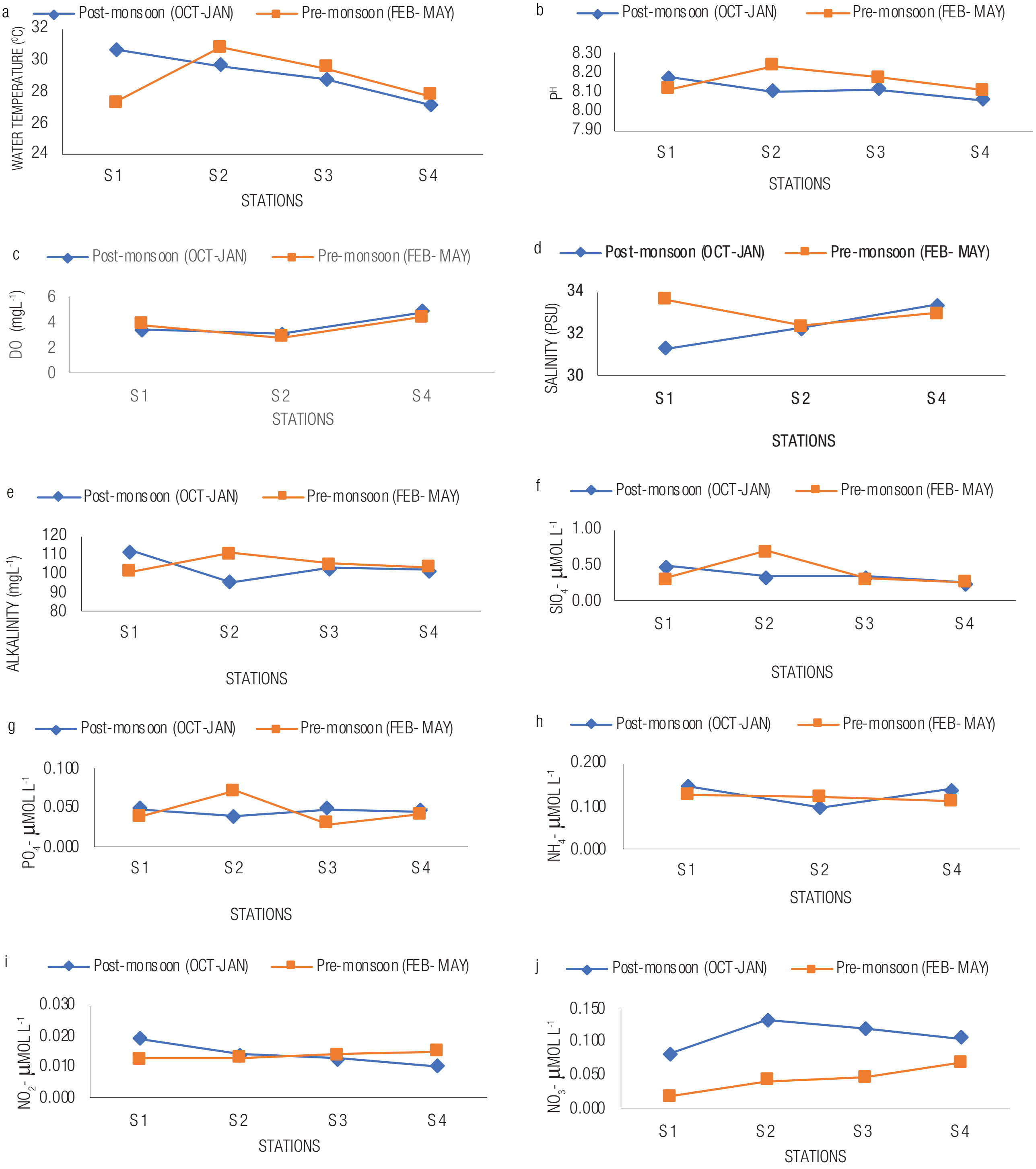


Fig. 2. Pre-monsoon and post-monsoon variations of different physico-chemical parameters. (a. Water temperature; b. pH; c. Dissolved oxygen; d, Salinity; e. Alkalinity; f. Silicate; g. Phosphate; h. Ammonia; i. Nitrite; j. Nitrate)

as *Coscinodiscus granii* and *Rhizosolenia gracillima* are more sensitive to silicate, Chl-a, pH and phosphate levels. The first two axes show a substantial amount of variation, showing 60.23% and 24.55% of the constrained inertia, respectively. Combining a total of 84.46% of the variation in physicochemical parameters and phytoplankton species relationships. Axis 1 has the highest eigenvalue (0.00526), explaining 60% of total inertia, indicating that it is the most significant gradient affecting phytoplankton distribution. While the second and third axes explain relatively small

Table 2. The CCA results of environmental variables against the dominant phytoplankton species

Species/ stations	Axis 1	Axis 2	Axis 3
Chaetoceros decipiens	-0.11634	2.57777	0.261015
Coscinodiscus granii	-2.24032	-1.27947	-0.7623
Ditylum brightwellii	0.984511	-0.24217	-0.2737
Ditylum sol	1.10213	-0.62287	0.824253
Planktoniella sol	-0.83354	0.584619	-0.02951
Rhizosolenia alata	-0.40183	0.322128	3.94091
Skeletonema costatum	0.811658	-0.54702	-1.04535
Thalassionema nitzschioides	0.423653	0.399008	-0.38492
Guinardia striata	2.23895	-1.37719	1.55404
Leptocylindrus danicus	-1.46959	0.131105	1.8925
Rhizosolenia gracillima	-0.41502	-1.01937	1.38052
Ceratium breve	-0.1303	-0.16608	0.113719
Ceratium furca	-1.51888	-0.72743	-0.21536
Ornithocercus sp.	-1.16968	-0.12111	-1.24119
S_1	-0.0449	-0.01177	0.049275
S_2	-0.07286	0.032793	-0.03877
S_3	0.047032	-0.0754	-0.02749
S_4	0.115877	0.053312	0.00734
Water temperature	0.97062	0.285239	-0.00775
DO	-0.93853	-0.38203	0.036113
Alkalinity	-0.95311	-0.23822	0.193521
Salinity	0.896163	0.160348	-0.39287
Nitrate	0.865477	0.238153	-0.41986
Nitrite	0.577097	-0.71074	-0.38923
Phosphate	-0.88191	-0.48721	0.102367
Silicate	-0.94281	-0.24205	0.228349
Eigenvalue	0.005256	0.002143	0.001328
% of constr. in.	60.23	24.55	15.22
% of total inertia	60	24.46	15.16

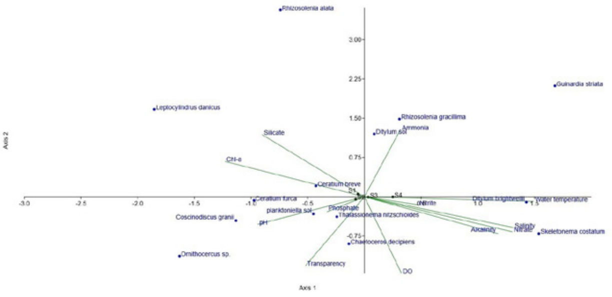


Fig. 3. The CCA bi-plot of dominant plankton species and water quality parameters

portions of variation, 24.55% and 15.22% of the constrained inertia, respectively. From October to May, the Jaigad coastal area's phytoplankton (cells L^{-1}) qualitative and quantitative distribution showed clear seasonal changes (Table 3).

Pearson correlation was performed to correlate each phytoplankton species with physicochemical parameters; it was found that phytoplankton species such as *Coscinodiscus granii* (-0.986, $P<0.05$), *Skeletonema costatum* (-0.955, $P<0.05$), *Ceratium furca* (-0.961, $P<0.05$) and *Ornithocercus* sp. (-0.956, $P<0.05$) showed significant negative correlation with water temperature. Phytoplankton species such as *Ditylum brightwellii* (0.993, $P<0.01$), *Skeletonema costatum* (0.972, $P<0.05$), *Leptocylindrus danicus* (0.981, $P<0.05$), *Rhizosolenia gracillima* (0.998, $P<0.01$) and *Ceratium breve* (0.982, $P<0.05$) showed significant positive correlation with pH. Dissolved oxygen and alkalinity levels were positively correlated with *Coscinodiscus granii* (0.994, $P<0.05$) and *Skeletonema costatum* (0.994, $P<0.05$); moreover, *Ceratium breve* (0.952, $P<0.05$), *Ceratium furca* (0.990, $P<0.05$) and *Ornithocercus* sp. (0.963, $P<0.05$) also showed significant positive correlation with alkalinity. *Coscinodiscus granii* (0.990, $P<0.01$), *Skeletonema costatum* (0.996, $P<0.01$), *Ceratium breve* (0.958, $P<0.05$), *Ceratium furca* (0.989, $P<0.05$) and *Ornithocercus* sp. (0.957, $P<0.05$) also showed significant positive correlation with silicate (Fig. 5).

At the beginning of the post-monsoon season, *Asterionella japonica*, *Cyclotella striata*, *Rhizosolenia alata*, *Skeletonema costatum*, *Corethron criophilum* and *Hemiaulus sinensis* were not present among phytoplankton; nevertheless, they began to increase from January in the pre-monsoon season. In comparison to other phytoplankton species at all sampling stations, the most prevalent ones during the pre-monsoon season were *Rhizosolenia gracillima*, *Skeletonema costatum*, *Planktoniella sol*, and *Thalassionema frauenfeldii*. *Skeletonema costatum* and *Thalassionema frauenfeldii* exhibited variability, with the maximum abundances (92.01 and 102.45 cells L^{-1}, respectively) occurring in May during the pre-monsoon season. *Biddulphia mobiliensis*, *Chaetoceros decipiens*, *Chaetoceros muelleri*, *Coscinodiscus granii*, *Ditylum brightwellii*, *Ditylum* sol, *Planktoniella sol*, *Pleurosigma* sp., *Thalassionema nitzschioides*, *Thalassionema frauenfeldii*, *Guinardia striata*, *Melosira* sp., and *Leptocylindrus danicus* were among the phytoplankton species that were observed during both pre-monsoon and post-monsoon seasons. *Ceratium breve* showed a downward trend among dinoflagellates, going from 7.80 cells L^{-1} in October to 1.01 cells L^{-1} in May. *C. furca* and *C. fucus* also showed a downward trend; at all stations during the same period, *C. fucus* decreased from 4.09 cells L^{-1} to 0.82 cells L^{-1}, and *C. furca* decreased from 6.48 cells L^{-1} in October to 0.75 cells L^{-1} in May. The abundance of *C. trichoceros* fluctuated, peaking in November (4.54 cells L^{-1})

Table 3. Phytoplankton species (cells L^{-1}) encountered during the present investigation (+ = 0-100, ++ = 100-500, +++ = >500 and–= absent)

Species	Post-monsoon				Pre-monsoon			
	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4
Diatoms								
Asterionella japonica	-	-	+	+	+	+	+	+
Biddulphia mobiliensis	+	+	+	+	+	+	+	+
Chaetoceros decipiens	+	+	+	+	+	+	+	+
Chaetoceros muelleri	+	++	+	+	+	+	++	+
Coscinodiscus granii	+	++	+	+	+	+	+	+
Cyclotella striata	-	-	-	+	+	+	+	+
Ditylum brightwellii	+	+	++	++	+	+	+	+
Ditylum sol	+	+	+	++	++	+	+	+
Navicula sp.	+	-	-	+	+	+	+	+
Planktoniella sol	+	++	++	++	++	++	++	+
Nitzschia sp.	+	-	-	+	+	+	+	+
Pleurosigma sp.	-	+	+	+	+	+	+	+
Rhizosolenia alata	-	-	+	+	+	+	+	+
Skeletonema costatum	-	-	-	+	++	++	+	+++
*Thalassionema nitzschioide*s	++	+	+	+	+	++	++	++
Thalassionema frauenfeldii	+	+	+	+	+	++	+	+++
Guinardia striata	+	++	+	+	+	+	+	+
Leptocylindrus danicus	+	+	+	+	+	+	++	+
Melosira sp.	+	+	+	+	+	+	+	+
Rhizosolenia gracillima	-	+	++	++	++	++	+	+
Lauderia annulata	-	+	+	+	+	+	+	+
Hemiaulus sinensis	-	-	-	+	+	+	+	+
Rhizosolenia calcaravis	-	-	+	+	+	+	+	+
Eucampia zodiacus	-	-	+	+	+	+	+	+
Corethron criophilum	-	-	-	+	+	+	+	+
Dinoflagellates								
Ceratium breve	++	++	++	+	+	+	+	+
Ceratium furca	++	++	+	+	+	+	+	+
Ceratium fucus	+	+	+	+	+	+	+	+
Ceratium trichoceros	+	+	+	+	+	+	+	+
Perinidium oceanicum	+	+	+	+	+	+	+	+
Ornithocercus sp.	+	++	++	+	+	+	+	+

and then gradually declining. A fluctuating trend was shown by *Perinidium oceanicum*, which peaked in March at 5.28 cells L^{-1} and had the lowest abundance in January at 1.13 cells L^{-1}. The Shannon-Weiner diversity index (H′ at $\log_2$) ranged from 1.08 to 3.31, and evenness (J′) ranged from 0.14 to 0.89 in the study region, with station S2 having the highest diversity index (H′ = 3.31) during the pre-monsoon period and station S2 having the lowest (H′ = 1.08) during the post-monsoon period. The dominance index ranged from 0.04 to 0.537, with the lowest and highest values occurring in January and May of the pre-monsoon season, respectively (Fig. 4).

Discussion

It is well known that phytoplankton are effective indicators of ecological changes and are highly sensitive to a variety of environmental stressors (Paerl *et al.,* 2007). Previous studies on phytoplankton in Mediterranean Sea estuaries found that environmental factors like temperature, salinity, water transparency, and nutrients significantly impact seasonal variation in phytoplankton abundance and diversity (Cetinic *et al.,* 2006; Buric *et al.,* 2007; Barbosa *et al.,* 2010; Jasprica *et al.,* 2012). The temporal fluctuation in phytoplankton biomass in eutrophic estuaries is similarly linked to light availability (Cloern, 1987; Mallin *et al.,* 1999). It has also been suggested that light limitation, salinity fluctuations, and water circulation may limit phytoplankton development (McLusky and Elliott, 2004). Seasonal variations in physical, chemical, and biological processes determine phytoplankton succession and abundance (Thillai *et al.,* 2010) and phytoplankton species composition is primarily determined by nutrient fluxes and environmental variables (Achary *et al.,* 2014).

The coastal areas face various threats from both natural and anthropogenic activities, which influence the physicochemical parameters and the distribution and abundance of phytoplankton as well as the survival of aquatic creatures, which are greatly influenced by physicochemical parameters such as water salinity, temperature, dissolved oxygen, and nutrients (Godhe *et al.,* 2015). Environmental factors like air temperature and the intensity of solar radiation could lead to changes in water temperature (Reddy, 2001). In the present study, high water temperature values were seen in the pre-monsoon season and slightly lower temperature values in the post-monsoon season. A similar trend was observed by Sushanth and Rajshekhar (2012) along the west coast of India; Anantharaj *et al.* (2013) and Rajthilak *et al.* (2016) along the Tamil Nadu, southeast coast of India; Tekade *et al.* (2017) along the Ratnagiri, west coast of India and Hardikar *et al.* (2017) along the Malvan, west coast of India. The mean water pH in the present study didn't vary much, and it ranged from 8.09 to 8.21. Nutrients like inorganic phosphate were present in high concentration (0.19 μmol L^{-1}) in the pre-monsoon period and lower (0.13 μmol L^{-1}) in the post-monsoon season. A similar trend was observed by Bhatkar *et al.* (2018) along the Malvan, west coast of India and Tekade *et al.* (2017) along the Ratnagiri, west coast of India.

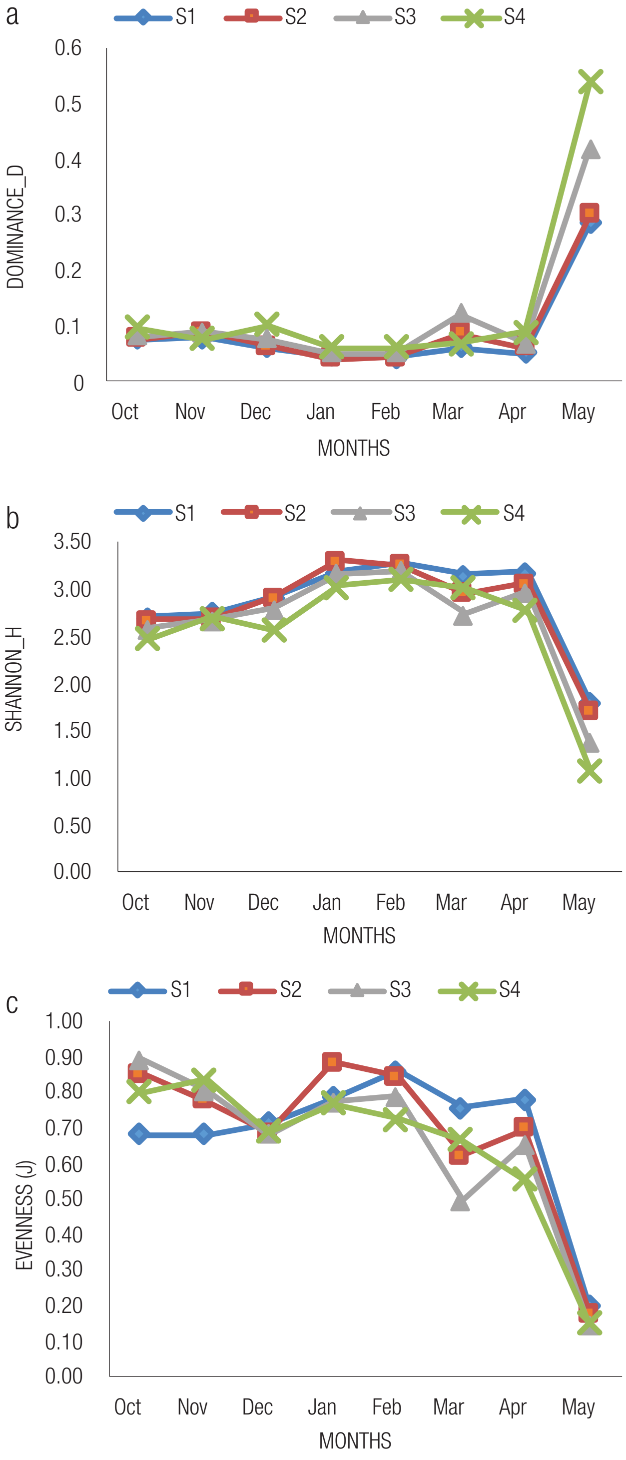
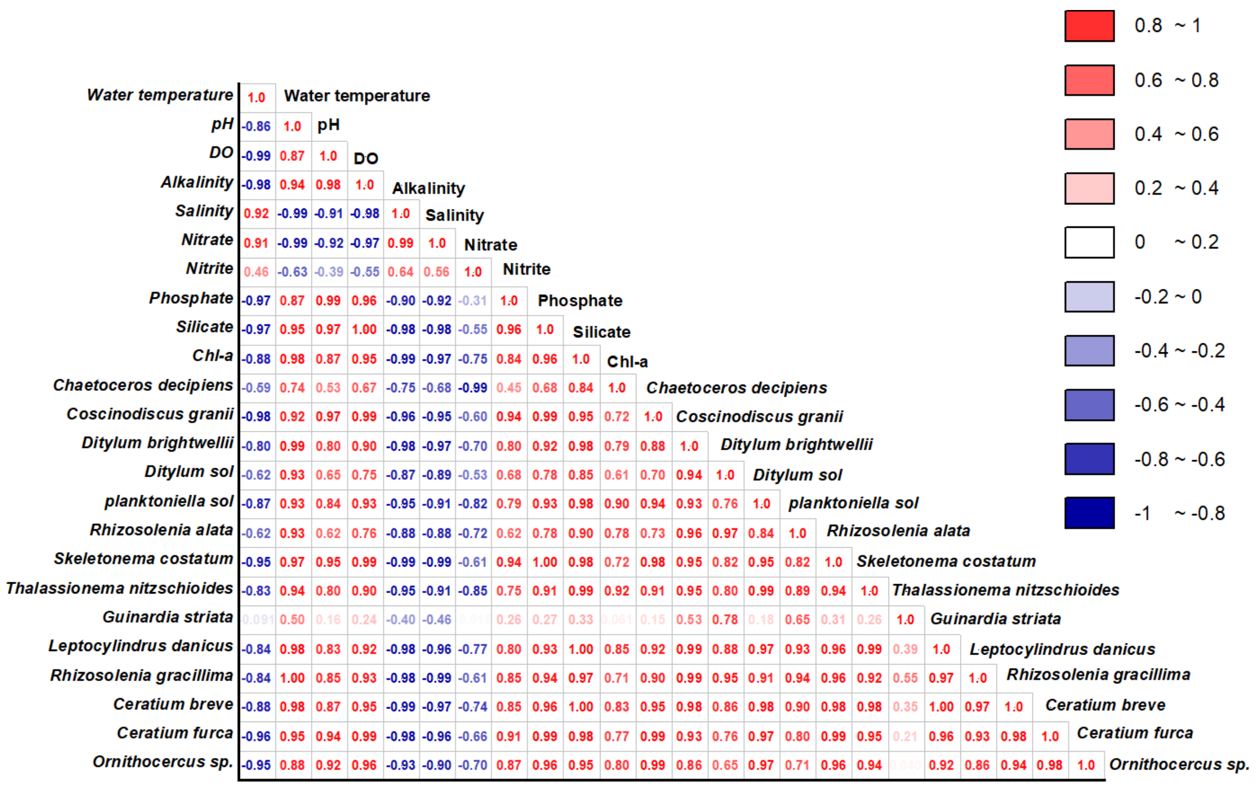


Fig. 4. Diversity indices, a) Dominance, b) Shannon Diversity, c.) Evenness

Silicate is one of the main nutrients that regulates the phytoplankton distribution in coastal waters. In the present study, the mean silicate concentration was recorded as maximum (0.45 μmol L^{-1}) in the pre-monsoon season and the lower concentration (0.23 μmol L^{-1}) in the post-monsoon season. Similarly high concentrations of silicate levels were observed by Sridhar *et al.* (2006) along the Palk Bay in the pre-monsoon period compared to the post-monsoon period. Sahu *et al.* (2012) and Anantharaj *et al.* (2013) also recorded a similar trend of silicate concentration along the southeast coast of India. In the present study, silicate showed a significant positive correlation with phytoplankton species such as *Coscinodiscus granii*, *Skeletonema costatum* and *Ornithocercus* sp.; similar findings were reported for these phytoplankton species by Conway *et al.* (1976); Taylor (1985); Egge and Aksnes (1992), Sun *et al.* (2007); Subhan *et al.* (2021) and Pradhan *et al.* (2023). In the present study, alkalinity was positively correlated with phytoplankton species such as *Ceratium breve, Ceratium furca, Skeletonema costatum* and *Coscinodiscus granii*. Taraldsvik and Myklestad (2000) observed that *S. costatum* is tolerant to a wide range of pH (6.5 to 8.5), though its growth declines under highly alkaline conditions; similarly, a positive correlation of *Ceratium* spp. with alkalinity was reported by Pradhan *et al.* (2023). However, when interpreting these statistical results, it is imperative to distinguish between correlation and causation. While Pearson's correlation reveals strong predictive relationships, increases in silicate or alkalinity do not unilaterally drive the observed phytoplankton distribution. Instead, these distributions reflect a complex interplay of unmeasured variables, including trace metal availability, microzooplankton grazing pressure, and localised coastal hydrodynamics (George *et al.,* 2012; Xin *et al.,* 2024).

According to the CCA biplot of physico-chemical parameters and phytoplankton species composition, which mostly reacted to seasonal variations in environmental variables. High abundance of *S. costatum* (102.45 cells L^{-1}) and *Thalassionema frauenfeldii* (92.01 cells L^{-1}) was observed in the pre-monsoon season, which could be due to favourable pre-monsoonal conditions and a rich supply of silicate and phosphate availability. The Shannon-Wiener diversity index (H′) is one of the most widely used indices for quantifying diversity. It can change with major ecological processes such as competition, predation, and succession, modifying the diversity through changes in evenness without any change in species richness (Stirling and Wilsey, 2001). This index can be used for monitoring the changes in ecosystems caused by pollution or eutrophication. According to Balloch *et al.* (1976), it is a good way to measure the quality of water. Using the Shannon-Wiener index, Hendley (1977) proposed a scale for measuring pollution in diatom communities: 0–1 for strong contamination, 1-2 for moderate pollution, 2-3 for marginal pollution, and 3-5 for incipient pollution. In the present study, the Shannon-Wiener index



	Water temperature	pH	DO	Alkalinity	Salinity	Nitrate	Nitrite	Phosphate	Silicate	Chl-a	*Chaetoceros decipiens*	*Coscinodiscus granii*	*Ditylum brightwellii*	*Ditylum sol*	*planktoniella sol*	*Rhizosolenia alata*	*Skeletonema costatum*	*Thalassionema nitzschioides*	*Guinardia striata*	*Leptocylindrus danicus*	*Rhizosolenia gracillima*	*Ceratium breve*	*Ceratium furca*	*Ornithocercus sp.*
Water temperature	1.0																							
pH	-0.86	1.0																						
DO	-0.99	0.87	1.0																					
Alkalinity	-0.98	0.94	0.98	1.0																				
Salinity	0.92	-0.99	-0.91	-0.98	1.0																			
Nitrate	0.91	-0.99	-0.92	-0.97	0.99	1.0																		
Nitrite	0.46	-0.63	-0.39	-0.55	0.64	0.56	1.0																	
Phosphate	-0.97	0.87	0.99	0.96	-0.90	-0.92	-0.31	1.0																
Silicate	-0.97	0.95	0.97	1.00	-0.98	-0.98	-0.55	0.96	1.0															
Chl-a	-0.88	0.98	0.87	0.95	-0.99	-0.97	-0.75	0.84	0.96	1.0														
Chaetoceros decipiens	-0.59	0.74	0.53	0.67	-0.75	-0.68	-0.99	0.45	0.68	0.84	1.0													
Coscinodiscus granii	-0.98	0.92	0.97	0.99	-0.96	-0.95	-0.60	0.94	0.99	0.95	0.72	1.0												
Ditylum brightwellii	-0.80	0.99	0.80	0.90	-0.98	-0.97	-0.70	0.80	0.92	0.98	0.79	0.88	1.0											
Ditylum sol	-0.62	0.93	0.65	0.75	-0.87	-0.89	-0.53	0.68	0.78	0.85	0.61	0.70	0.94	1.0										
planktoniella sol	-0.87	0.93	0.84	0.93	-0.95	-0.91	-0.82	0.79	0.93	0.98	0.90	0.94	0.93	0.76	1.0									
Rhizosolenia alata	-0.62	0.93	0.62	0.76	-0.88	-0.88	-0.72	0.62	0.78	0.90	0.78	0.73	0.96	0.97	0.84	1.0								
Skeletonema costatum	-0.95	0.97	0.95	0.99	-0.99	-0.99	-0.61	0.94	1.00	0.98	0.72	0.98	0.95	0.82	0.95	0.82	1.0							
Thalassionema nitzschioides	-0.83	0.94	0.80	0.90	-0.95	-0.91	-0.85	0.75	0.91	0.99	0.92	0.91	0.95	0.80	0.99	0.89	0.94	1.0						
Guinardia striata	-0.091	0.50	0.16	0.24	-0.40	-0.46	-0.015	0.26	0.27	0.33	0.061	0.15	0.53	0.78	0.18	0.65	0.31	0.26	1.0					
Leptocylindrus danicus	-0.84	0.98	0.83	0.92	-0.98	-0.96	-0.77	0.80	0.93	1.00	0.85	0.92	0.99	0.88	0.97	0.93	0.96	0.99	0.39	1.0				
Rhizosolenia gracillima	-0.84	1.00	0.85	0.93	-0.98	-0.99	-0.61	0.85	0.94	0.97	0.71	0.90	0.99	0.95	0.91	0.94	0.96	0.92	0.55	0.97	1.0			
Ceratium breve	-0.88	0.98	0.87	0.95	-0.99	-0.97	-0.74	0.85	0.96	1.00	0.83	0.95	0.98	0.86	0.98	0.90	0.98	0.98	0.35	1.00	0.97	1.0		
Ceratium furca	-0.96	0.95	0.94	0.99	-0.98	-0.96	-0.66	0.91	0.99	0.98	0.77	0.99	0.93	0.76	0.97	0.80	0.99	0.95	0.21	0.96	0.93	0.98	1.0	
Ornithocercus sp.	-0.95	0.88	0.92	0.96	-0.93	-0.90	-0.70	0.87	0.96	0.95	0.80	0.99	0.86	0.65	0.97	0.71	0.96	0.94	0.040	0.92	0.86	0.94	0.98	1.0

🟥	0.8 ~ 1
🟥	0.6 ~ 0.8
🟥	0.4 ~ 0.6
🟥	0.2 ~ 0.4
☐	0 ~ 0.2
🟦	-0.2 ~ 0
🟦	-0.4 ~ -0.2
🟦	-0.6 ~ -0.4
🟦	-0.8 ~ -0.6
🟦	-1 ~ -0.8

Fig. 5. Pearson's correlation analysis of dominant plankton species and physicochemical parameters

ranged from 1.08 to 3.31, where the maximum index was recorded at stations S1 and S2, while the lower index value was recorded at stations S3 and S4, which were farther from the coastal area. The nearshore enrichment along the Ratnagiri coast, driven by estuarine runoff and stratification, supports heterogeneous communities exploiting varied nutrient niches, mirroring patterns in tropical west coast Indian estuaries. In contrast, stations (S3–S4), which were at 36 m depth, exhibit homogenised assemblages characteristic of Arabian Sea dynamics, where monsoon-driven upwelling, shelf-slope fronts, and nutrient dilution promote diatom-dominated but less diverse blooms, consistent with regional oceanographic processes (Minu and Prabhakaran, 2025). These gradients align with west coast India trends, where pre-monsoon warming and land-derived nutrients favour coastal peaks, while post-monsoon mixing extends productivity offshore (Mhatre *et al.*, 2022; Naqvi *et al.,* 2010).

Conclusion

The present study showed that phytoplankton community structure in the coastal waters of Jaigad, India's west coast, was mainly influenced by silicate and alkalinity, while dissolved oxygen, nitrate and nitrite had comparatively lesser effects. Diatoms dominated throughout the sampling period, with 26 diatom and 6 dinoflagellate species recorded. *Skeletonema costatum* and *Thalassionema frauenfeldii* were the most abundant species. Canonical correspondence analysis confirmed the strong role of silicate and alkalinity in shaping phytoplankton distribution. Diversity indices also indicated possible anthropogenic influence at some stations, likely linked to harbour and port activities. Overall, the findings provide a useful baseline for monitoring phytoplankton dynamics and supporting sustainable coastal ecosystem management.

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Author contributions

Conceptualisation: PJA, ADA; Methodology: PJA, ADA; Data Collection: PJA, MSS, PVN; Data Analysis: PJA, ADA; Writing Original Draft: PJA, PVN; Writing Review and Editing: PJA, PVN; Supervision: RHR, SWB, SAJ

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of samples/ protected environments.

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Publisher's note

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Spatial distribution of selected heavy metals and their probable ecological risk in coastal sediments of Tuticorin, southeast coast of India

P. S. Asha[1]*, R. Lavanya[3], A. Usharani[2], B. Muniswaran Ramar[2] and Reeta Jayasankar[3]
[1]Regional Centre of ICAR-Central Marine Fisheries Research Institute, Vizhinjam- 695 521, Kerala, India.
[2]Regional Station of ICAR-Central Marine Fisheries Research Institute, Tuticorin-628 001, Tamil Nadu, India.
[3]ICAR-Central Marine Fisheries Research Institute, Kochi-682 018, Kerala, India.

*Correspondence e-mail: ashasanil@gamil.com
ORCiD: http://orcid.org/0000-0002-6514-7375

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Original Article

Abstract

The rise in industrial and urban activities has exacerbated soil contamination with metals, making it a pressing global issue. In this study, eight stations (St.1 to 8) were identified to assess the concentrations of heavy metals such as lead (Pb), cadmium (Cd), nickel (Ni), and mercury (Hg) in the sediments of the Tuticorin coast across four seasons: Monsoon, Post-monsoon, Summer, and Pre-monsoon. The dried, finely ground sediment samples were digested and analysed for heavy metals using standard procedures. Elevated mean concentrations of Cd (4.95±0.28 μg g^{-1}) and Hg (0.26±0.06 μg g^{-1}) were recorded at St.1. At the same time, Ni (35.59±4.16 μg g^{-1}) and Pb (26.42±10.1 μg g^{-1}) showed maximum levels at the St.2. According to the various Sediment Quality Guidelines (SQGs), the study indicated a low probability of adverse effects from Hg, Ni, and Pb along the Tuticorin coast. However, Cd concentrations pose a probable ecological risk with values exceeding the Probable Effect Level (PEL) to Severe Effect Level (SEL) in most stations, indicating potential impact on the benthic ecosystem. A moderate pollution level of Cd (<6) was observed at all stations as per the Environmental Protection Agency (EPA) guidelines. Except for Cd, concentrations of all other metals remained within the PEL thresholds prescribed by the Canadian Environmental Quality guidelines for the protection of aquatic life. The highest pollution index level was noticed at St. 2 and St.1, which reflects the possible anthropogenic impacts. The results of the study emphasise the urgent need for targeted mitigation measures to reduce metal contamination, especially that of Cd, along the Tuticorin coastal belt.

Keywords: *Mitigation measures, Probable Effect Level, Sediment Quality Guidelines, Severe Effect Level*

Introduction

The high persistence and resistance to natural degradation make heavy metal pollution a significant environmental challenge globally. Heavy metals usually stem from both geogenic and anthropogenic sources in the marine ecosystem (Beier *et al*., 2022) and serve as a reservoir to release these metals in changing environmental conditions. Usually, these metals pose a threat to the aquatic food chain through bioaccumulation and biomagnification, and ultimately affect human health. Soil contamination by heavy metals arises from sources such as industrial waste, urban effluents, wastewater, mining activities, and prolonged fertiliser application. The intensification of industrial and urban activities has aggravated soil contamination with metals. Non-essential toxic metals, including cadmium (Cd), mercury (Hg), lead (Pb), and nickel (Ni), are particularly harmful, even at low concentrations (Cohen *et al*., 2001); these are classified as toxic heavy metals.

An industrial town like Tuticorin, in the Gulf of Mannar, has many major and minor industries along its coast. The effluent discharges from various units involved in the production of cotton, staple yarn, caustic soda, PVC resin, fertilisers, soda ash, and liquid carbon dioxide are the primary sources of heavy metal pollution. Earlier studies have identified industrial activities, including fertiliser, chemical, and allied coastal industries, along with urban and port-related inputs, as possible contributors to metal contamination in the Tuticorin coastal environment (Ganesan and Kannan, 1995; Palanichamy and Rajendran, 2000; Asha *et al*., 2010; Selvam *et al*., 2015; Vinothkannan *et al*., 2022).

The objective of the present study is to assess the level of four toxic heavy metals, such as nickel (Ni), cadmium (Cd), lead (Pb) and mercury (Hg) in the surface sediments of eight stations of the Tuticorin coast. The research will establish a benchmark on the impact of anthropogenic activities on the level of four heavy metals and their potential ecological risk along the coastal zone. The findings will, in turn, be helpful in future research on similar aspects and also to formulate appropriate management measures for safeguarding the coastal resources in the region.

Material and methods

Study area

A baseline survey was conducted along the coastal belt of Tuticorin in both northern and southern directions; consequently, eight stations were identified to assess the heavy metal load. Four stations (St. 1, 2, 3, and 4) were selected along the southern coast, while four stations (St. 5, 6, 7, and 8) were identified along the northern coast. The locations of the sampling stations are shown in Fig.1. Station 1 (St.1) was the coastal belt situated north of Hare Island (08°47'.039'N; 078°11'.136'E), and Station 2 (St.2) was located south of Hare Island (08°45'.154'N; 078°11'.609'E). Station 3 (St.3) was positioned in proximity to the Muthiahpuram coast (08°43'.587'N; 078°09'.495'E), and station 4 (St.4) was fixed near the Tiruchendur coast (08°37'.610'N; 078°07'.624'E). Station 5 (St.5) was located north of the Threspuram coast (08°47'.867'N; 078°09'.674'E), and station 6 (St.6) was positioned south of Threspuram (08°48'.717'N; 078°09'.820'E). Station 7 (St.7) was situated along the coastal areas of Siluvaipatti (08°50'.596'N; 078°10'.025'E), whereas station 8 (St.8) was close to the Pattanamaruthur coast (08°54'.329'N; 078°10'.786'E).

Sample collection, processing and estimation of heavy metals

Samples were collected from selected stations over four seasons: Monsoon (November, December, and January), Post-monsoon (February, March, and April), Summer (May, June, and July), and Pre-monsoon (August, September, and October). In total, 32 sediment samples were collected from the study locations

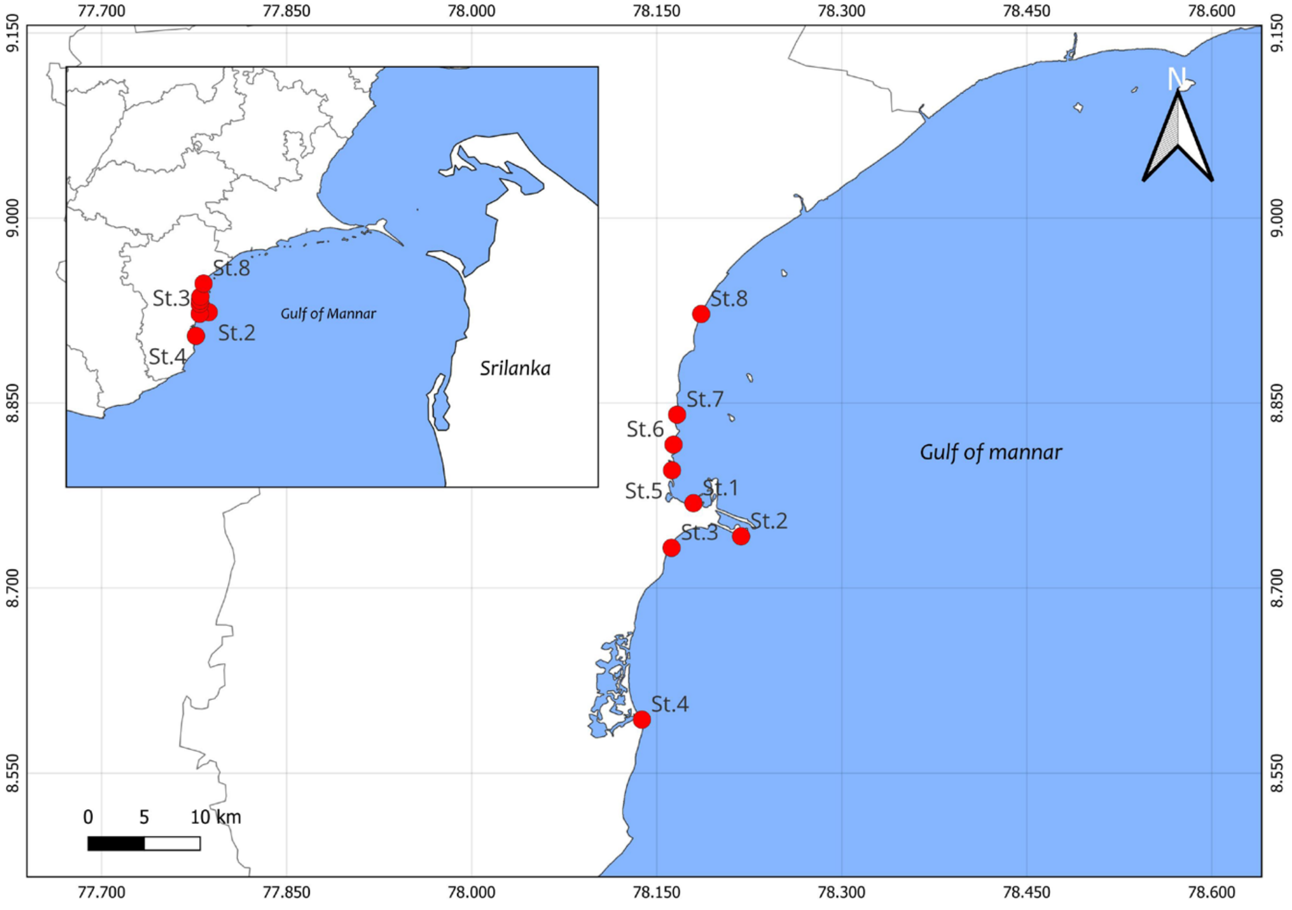

Fig. 1. Location of the sampling stations

across these four seasons. Surface sediment samples were obtained from the top two cm of the intertidal zones using 3.5-inch outer diameter PVC pipes. The collected sediment samples were dried at room temperature, ground to a fine powder using an agate mortar and pestle, and then sieved through a 63-μm sieve. One gram of the sieved sample was acid-digested (Dalziel and Baker,1984) and filtered with Whatman Grade 542 filter paper to remove residual contaminants. The filtered samples were made up to 100 ml and analysed in triplicate using an atomic absorption spectrophotometer (AAS) Thermo Fisher Scientific–AAS ICE – 3300 AA SPECTRO, by Flame analysis and Hg by cold vapour technique using the vapour generator –VP 100, which is attached to the AAS. The accuracy of the analytical procedure was estimated using the Standard Reference Material for sediment, SIGMA-ALDRICH (USA) SQC001-30G. The analysis precision was within 10%, and the metal recovery from the samples was>90%. All reagents used in the procedures were prepared with metal-free, double-distilled water and analytical grade chemicals. Additionally, the instrument was rinsed with double-distilled water after each use.

Statistical analysis and ecological risk assessment

The estimated mean metal concentrations were used to interpret the results. The significant differences in heavy metal concentrations among sampling sites at the 0.05 level were determined by one-way ANOVA using SPSS software (version 22; Chicago, USA). Different sets of international Sediment Quality Guidelines (SQGs) for marine and estuarine ecosystems were used to evaluate the potential risks posed by heavy metal concentrations in sediments (Long and Morgan 1990; Macdonald *et al.*,1996; Engler *et al.*, 2005). The SQGs of the Threshold Effect Level (TEL), Probable Effect Level (PEL), and Severe Effect Level (SEL), which indicate the various ranges of these guidelines (Long *et al.*, 2023), were compared with the estimated concentrations of various heavy metals at all sampling stations. Pollution Load Index (PLI) was used to assess the level of sediment deterioration and to determine whether the target heavy metals originated from natural or anthropogenic sources (Angulo, 1996). The PLI can be calculated by the following formula.

Where n is the number of metals, CF is the contamination factor, which is the ratio of measured concentrations of target metals in the sediment and their original background (geochemical) concentrations. Standard pre-industrial reference levels of target metals in sediment (in mg/kg) are 6.8 for Ni, 1.0 for Cd, 70 for Pb and 0.3 for Hg. The following classes of PLI (Kowalska *et al.,* 2018) were used for interpretation: 1 > PLI – no contamination, PLI = 1 – only baseline levels of contamination, 1 < PLI – deterioration of site quality.

Results

Spatial variation of heavy metal concentration

Notably, there was a considerable fluctuation in Nickel (Ni) concentrations among the stations. The Ni concentrations were relatively higher at Sts. 1, 2, and 3 during the post-monsoon period and lower at St. 5, 6, 7 and 8 (Table 3). The Ni concentrations varied from 20.04 to 39.83 μg g^{-1} at St. 1, 29.45 to 47.87 μg g^{-1} at St.2, and 18.05 to 56.01 μg g^{-1} at St.3. The highest mean value, recorded at St.2, was 35.59 ± 4.16 μg g^{-1} (Fig. 2 a), followed by 34.28±8.59 μg g^{-1} at St.3.

Table 1. Seasonal variation in the heavy metal concentrations in the sediments of the Tuticorin coast

Stations	Heavy metal concentrations (μg g^{-1}) during different seasons															
	Ni				Cd				Pb				Hg			
	MON	POM	SUM	PRM	MON	POM	SUM	PRM	MON	POM	SUM	PRM	MON	POM	SUM	PRM
1	20.04	39.83	21.04	36.75	4.88	5.32	5.42	4.18	30.42	10.51	21.88	27.84	0.11	0.22	0.35	0.35
2	32.57	32.48	47.87	29.45	4.56	4.92	4.37	5.49	26.43	3.79	22.62	52.82	0.09	0.11	0.08	0.09
3	23.34	56.01	18.05	39.70	4.82	4.15	4.27	4.71	0.00	0.00	16.19	0.00	0.07	0.06	0.06	0.07
4	28.92	19.76	28.85	25.63	4.54	4.39	4.44	3.86	28.96	1.00	5.38	34.12	0.03	0.05	0.05	0.05
5	18.99	13.85	10.12	16.34	4.54	4.71	4.14	4.24	6.95	10.03	12.80	1.00	0.05	0.05	0.04	0.05
6	10.84	12.63	15.05	18.76	4.46	4.39	4.90	5.06	1.46	2.80	3.04	5.81	0.04	0.05	0.04	0.04
7	22.97	9.64	19.80	16.12	4.88	2.99	4.72	4.07	1.39	0.74	1.22	0.96	0.04	0.04	0.04	0.05
8	0.00	18.93	17.26	18.44	4.76	4.54	4.39	4.54	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.04

MON-Monsoon, POM-Post Monsoon, SUM-Summer, PRM –Pre Monsoon

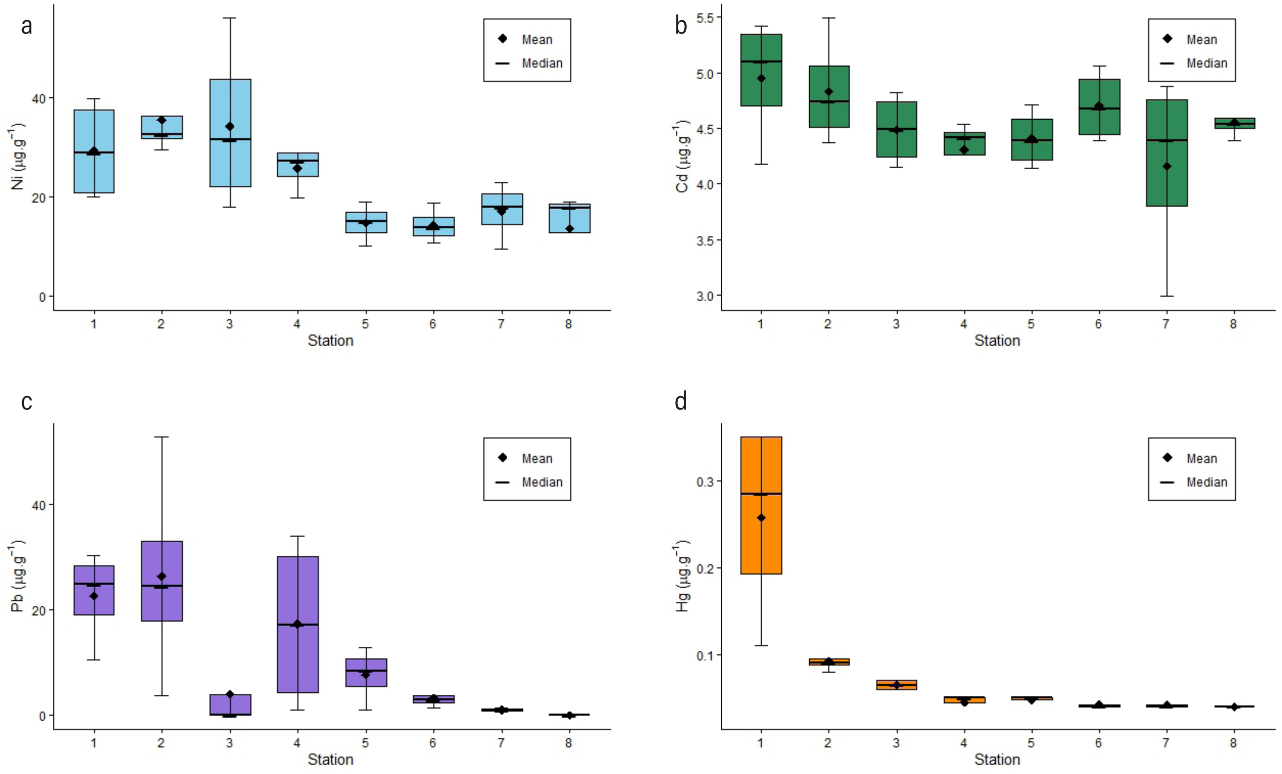

Fig. 2. Concentrations (mean±SE) of heavy metals (a. Ni; b. Cd; c. Pb; and d. Hg) in the coastal sediments of Tuticorin across eight sampling stations

Regarding Cadmium (Cd) concentrations, fluctuations were minimal between stations, with values ranging from a low of 2.99 µg g^{-1} at St.7 during the post-monsoon period to a high of 5.498 µg g^{-1} at St.2 in the Summer (Table 1). The highest mean concentration was 4.84 ± 0.25 µg g^{-1} at St.1, while the lowest was 4.17z0.43 µg g^{-1} at St.7 (Fig. 2 b).

Lead concentrations were notably higher at St.1 and 2, below the detectable limits at St.8 for all seasons, and could only be detected during the Summer at St.4. The lead levels varied between 10.51 and 30.42 µg g^{-1} at St.1, 3.79 and 52.82 µg g^{-1} at St2, and 1 to 34.12 µg g^{-1} at St.4. The maximum mean concentration of 26.4±10.1 µg g^{-1} was observed at St. 2 (Fig. 2 c).

With regard to mercury concentrations, fluctuations among St.4, 5, 6, 7, and 8 were not significant, and levels were exceptionally higher at St.1, where the Hg concentrations ranged from 0.11 to 0.35µg g^{-1}, with the highest mean concentration being 0.26±0.06 µg g^{-1} (Fig. 2 d).

Ecological risk assessment based on Sediment Quality Guidelines (SQGs)

The levels of heavy metals in the sediments according to the Sediment Quality guidelines are given in Table 2. Accordingly, most stations showed Ni concentrations causing minor adverse effects as the levels were within the range of TEL to PEL (Fig. 3 a). At the same time, significant negative impact levels were anticipated only at St.2 and 3 during the summer and post-monsoon seasons. Cd concentration causing a significant negative impact on the benthic ecosystem (PEL to SEL) was observed in most stations, including Sts. 1, 2, 3, 4, 5, 6, and 8 (Fig. 3 b). The maximum impact was observed at St.2 and 8. Among the stations, the seasonal variations in Pb levels were significantly high at St.2 and 4 and moderate at Sts. 1 and 5. It was below the threshold effect level (TEL), causing no harm to the benthic fauna at all the remaining stations. during the rest of the season (Fig. 3 c). Minor adverse level effects of Hg were reported at St.1 during the post-monsoon, summer, and pre-monsoon seasons. For all the other stations, Hg was below the threshold effect level (Fig. 3 d). Thus, the study indicated a low probability of adverse

Table 2. Heavy metal levels according to the Sediment Quality Guidelines (SQG) for sediment samples

Metals	Not polluted	Minor adverse effect	Significant negative impact	Heavily polluted
Ni	<5.90	5.90-42.8	42.8-75	>75
Cd	<0.68	0.68-4.21	4.21-10	>10
Pb	<30.20	30.2-112.20	112.2-250	>250
Hg	<0.174	0.174-0.486	0.486-2	>2

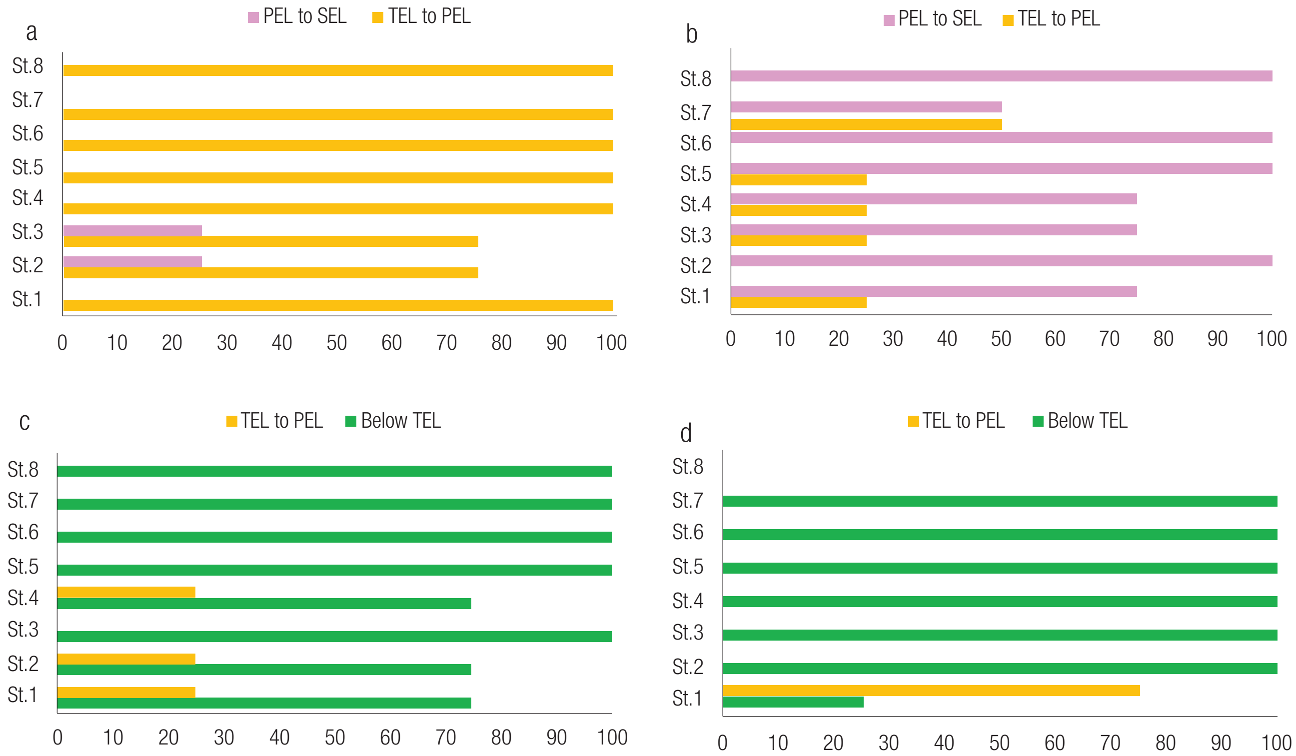

Fig. 3. Variation in the Sediment Quality Guidelines concentration of heavy metals (a. Ni, b. Cd, c. Pb and d. Hg) at sampling stations

effects from heavy metals such as mercury (Hg), nickel (Ni), and lead (Pb). Specifically, the analysis revealed a very low risk for Hg, with only 9.4% of samples exceeding the permissible environmental levels (PEL); for Ni, only 6.3% surpassed the PEL; and for Pb, again, 9.4% exceeded the PEL. In stark contrast, the risks associated with cadmium (Cd) were notably high, as 93.8% of the analysed samples surpassed the PEL.

The pollution load index was derived from the contamination factor for each metal (Fig. 4 a, b, c and d) and from the estimation of the pollution index level (PLI). It was found that the PLI was maximum for St.1, followed by St.2, and the least was noticed for St.8 (Fig. 4 e). Consequently, the present evaluation indicated that there was no significant contamination level, except for Cd in the coastal sediment along the Tuticorin coast.

Comparison with regulatory standards

The estimated levels of heavy metal concentrations at sampling stations were compared with Environment Protection Agency (US EPA, 2008) guidelines, as shown in Table 3. The Ni concentration was within the range of moderate pollution (20-50 ppm) at St.1, 2, 3 and 4. Notably, it was in a highly polluted state (>50 ppm) at St.3 during the post-monsoon season, whereas the unpolluted range of Ni status was reported at St.5, 6, 7, and 8. Cd concentration was notable at all the sampling Stations, which reported a moderate pollution level with Cd (<6) at all the stations. Accordingly, the Pb pollution was not so severe at Tuticorin, as in most of the stations, it was below 40 ppm; it can be considered as unpolluted and a moderately polluted condition was noticed only at St.2 during the pre-monsoon season, which reported a value between 40 – 60 ppm. Mercury levels at all the sampling stations were the lowest as they were not polluted at ≥ 1.0 ppm throughout. All other metal concentrations, except Cd, fell within the levels prescribed by the Canadian Environmental Quality guidelines aimed at protecting aquatic life. An ANOVA test revealed significant differences in the levels of Ni ($p > 0.05$) and Hg ($p > 0.000$) between the sampling stations. However, none of the samples exhibited significant variations across different seasons.

Table 3. Heavy metal levels according to the EPA guidelines for coastal sediment

Metals	Not polluted	Moderately polluted	Heavily polluted	Average In the present study
Pb	<40	40-60	>60	27.98
Cd	-	<6	>6	4.60
Ni	<20	20-50	>50	15.64
Hg	≥	-	>1.0	0.10

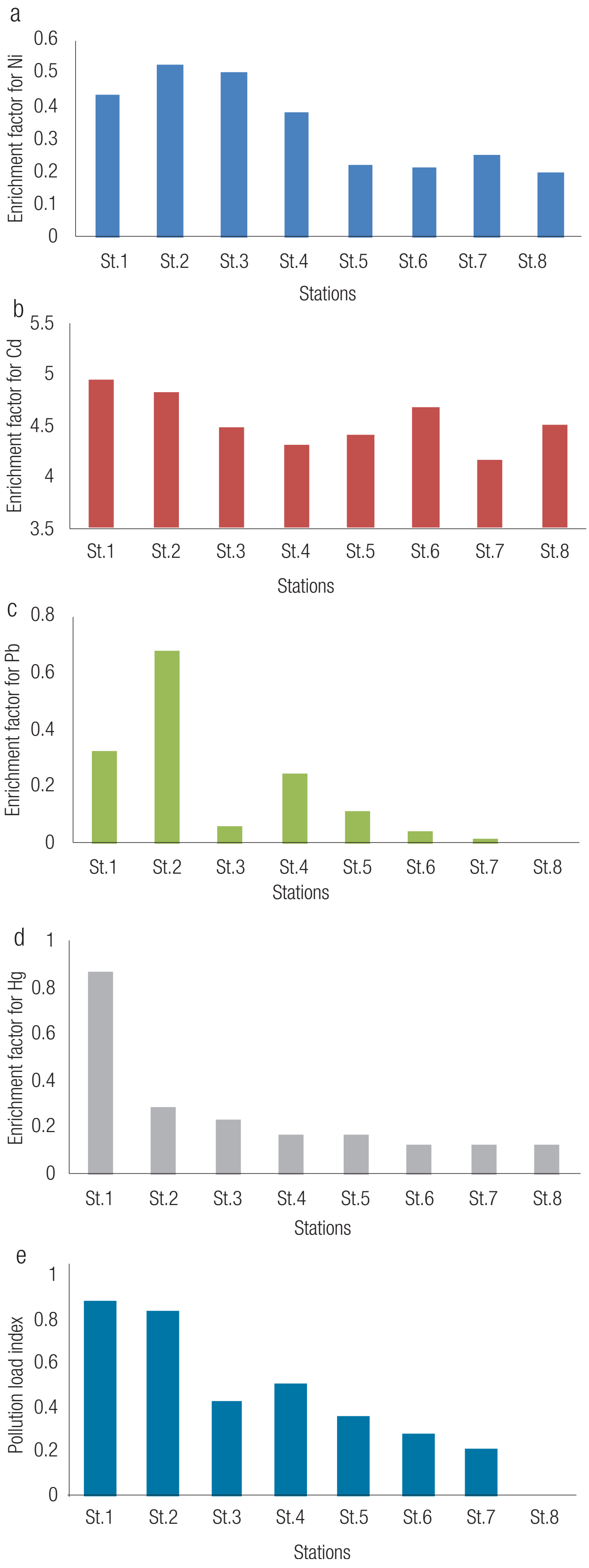

Fig. 4. Enrichment factor for heavy metals (a. Ni, b. Cd, c. Pb and d. Hg) and e. Pollution load index at sampling stations

Discussion

The present study highlighted the presence of four heavy metals in the coastal sediment of eight stations along the Tuticorin industrial zone. The concentration of Ni was found to vary significantly across stations, with the highest mean values observed at St. 2 and 3. Comparable values of Ni in coastal sediments have been noted along the coast of Eastern Tamil Nadu (Harikrishnan *et al.,* 2017), the Gulf of Mannar (Jonathan *et al*., 2006), and the Palk Strait (Kasilingam *et al*., 2016). In the present study, exceptionally high concentrations of Ni (56.01ppm) at St.3 during the post-monsoon season clearly indicated the monsoon effect on metal transportation and accumulation in this region, as reported by Wang *et al.* (2013) and El Nemr *et al.* (2016).

The concentration of Cadmium (Cd) in the sediment samples of the study locations was distinctively higher, as 93.8% of them exceeded the Probable Effect Level (PEL), which warns of the probability of negative biological impact. Higher concentrations of Cd in the coastal sediment of Tuticorin and the Gulf of Mannar were earlier reported by many researchers (Asha *et al*., 2010; Magesh *et al*., 2013; Selvam *et al*., 2015; Harikrishnan *et al*.,2017). High Cd concentrations at multiple sampling points indicate the possible influence of surrounding industries but require source-specific confirmation. In the present study, the maximum concentration of Cd was observed at St. 1, indicating the crucial role of anthropogenic impact. Similar findings of a significant source of Cd pollution in the coastal sediments of the Indian coast have been reported previously (Agrawal *et al*., 2010; Patel *et al.,* 2017; Gavhane and Pagar, 2025; Mandal and Raj, 2025). Cd is also considered a common impurity in phosphate fertilisers and effluents from fertiliser industries and other anthropogenic discharges, which have been reported to cause significant damage to coastal ecosystems (Robin *et al*., 2012; Naik *et al*., 2023; Veluchamy *et al*., 2024; Nagarajan *et al*., 2024).

The Lead (Pb) concentrations were below the Threshold Effect Level (TEL) in the majority of the stations; however, significantly higher levels were noticed at Sts. 1, 2, and 4, particularly during the monsoon and pre-monsoon periods. These increases may be attributed to the anthropogenic influences and remobilisation from polluted stations (Dassenakis *et al.,* 1997). The Pb concentration reported in the present study is comparable with that observed by Kasilingam *et al.* (2016) in the Palk Strait sediment. Mercury (Hg) concentration was comparatively higher at St.1, especially during the summer and pre-monsoon season. The increased Hg values at St.1 may be attributed to anthropogenic inputs. Comparable results of Hg concentrations were reported by Veluchamy *et al.* (2024) along south-eastern India and Naik *et al.* (2023) along south-western Bay of Bengal. Although at the majority of the stations, the mercury level was very low and below the Threshold Effect Level (TEL), hence ongoing monitoring is still required owing to its persistent nature and the capacity for bio-magnification (UNEP, 2013).

In general, the studies reiterated the possible role of anthropogenic sources in the metal pollution of Tuticorin coastal sediments. Relatively lower metal values were noted at stations north of Tuticorin (St. 5, 6, 7, and 8), and the least detected station was St.8, as evidenced by the below-detectable-limit values of Pb during all seasons and Ni during the monsoon period, probably due to less anthropogenic impact, minimising ecological damage.

The studies conducted on similar aspects in the region (Ganesan and Kannan, 1995; Magesh *et al.*, 2013; Selvam *et al.*, 2015; Vinothkannan *et al.*, 2022) also identified that industrial, port-related activities, untreated sewage, and urban runoff are significant sources of heavy metal contamination along the Tuticorin coast. From different parts of the World, other industrialised coastal belts, such as the Pearl River Delta (Zhang *et al.*, 2010), the Red Sea (El-Said *et al.*, 2014), and Mumbai's Thane Creek (Pekey *et al.*, 2006), have reported similar spatial trends.

In this study, slight seasonal variations, especially in Ni concentrations during the post-monsoon period, were observed; ANOVA tests did not reveal significant seasonal variations in metal concentrations. These variations might be due to the redistribution of pollutants along the shore and the drift of coastal currents and monsoonal runoff. The impact of hydrodynamics and sediment transport on the distribution of heavy metal contaminants has been reported earlier (Palanichamy and Rajendran, 2000). Except for Cd, the study showed that the concentrations of other metals, such as Pb, Ni, and Hg, were within the limits prescribed by the Canadian Environmental Quality Guidelines (CEQG) for sediment quality. According to the Sediment Quality Guidelines (SQGs), Cadmium (Cd) was identified as the most concerning pollutant in this ecosystem. At the same time, nickel (Ni), lead (Pb), and mercury (Hg) presented moderate risks. This pattern is consistent with findings from other Indian coastal sediments (Chatterjee *et al.*, 2009; Sahoo and Swain, 2023).

Based on the estimated mean Probable Effect Level (PEL), metals such as Hg, Ni, and Pb exhibited low ecological risk along the Tuticorin coast, whereas Cd levels indicated a comparatively higher potential for ecological concern. The contamination factor (CF) and the Pollution Load Index (PLI) estimate further support these observations, indicating the need for continuous monitoring and appropriate remediation efforts across the region.

This study underscores the spatial differences in the presence of metals in sediments along the southern and northern coastal areas of Tuticorin. These findings indicate possible anthropogenic influences as a source of heavy metal accumulation in this area. High levels of Cd, Pb, and Hg at St.1; elevated levels of Ni, Pb, and Cd at St.2; and a notable increase in Ni at St. 3 highlight the possible role of anthropogenic disturbances in these areas. The consistently high Cd levels across all stations also emphasise the need for remedial actions to mitigate the potential hazards. In contrast, the northern coastal sediments exhibited comparatively lower metal concentrations, suggesting limited anthropogenic influence pressure in this region compared to that in the southern coastal sediments.

Overall, the findings provide a valuable scientific baseline for future environmental monitoring, ecological risk assessment, and policy formulation aimed at sustainable coastal zone management. Continuous monitoring, stricter effluent management, and implementation of environmentally sustainable industrial practices are essential to prevent further accumulation of toxic metals and safeguard the ecological health of the Tuticorin coastal ecosystem. Additionally, the use of appropriate bioremediation strategies (Eggleton and Thomas, 2004; Li *et al.*, 2015) and supplementary ecotoxicological research involving local biota is advised. Given the impact of coastal currents and sediment movement, this study also emphasises the necessity for enhanced surveillance measures and community awareness programs along the Tuticorin coastline.

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Author contributions

Conceptualisation: PSA, JR; Methodology: PSA, DP, LR, JR; Data Collection: PSA, AU, MR, LR; Data Analysis: PSA; Writing Original Draft: PSA; Supervision: KSS, JR, DP.

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of sensitive samples/ protected environments.

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Publisher's note

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Integrative taxonomy of genus *Strongylura* van Hasselt, 1824 (Belonidae) from Indian waters

Toji Thomas[1,2]*, E. M. Abdussamad[1] and Badarul Sijad[1]
[1]ICAR-Central Marine Fisheries Research Institute, Kochi- 682 018, Kerala, India.
[2]Mangalore University, Mangalagangotri–574 199, Karnataka, India.

*Correspondence e-mail: tojithomas1992@gmail.com
ORCiD: https://orcid.org/0000-0003-3184-7645

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Original Article

Abstract

The genus *Strongylura* (Belonidae) comprises several morphologically similar species, which have historically led to taxonomic ambiguities, particularly in the Indo-Pacific region. The present study addresses these challenges through an integrative taxonomic assessment of three closely related species-*Strongylura incisa*, *S. leiurus,* and *S. strongylura*-collected from Indian waters between 2021 and 2023. Detailed morphometric and meristic analyses were conducted along with mitochondrial DNA (COI) sequencing to examine species boundaries. The results clearly support the distinctiveness of each species. *S. incisa* is characterised by a slender body, relatively longer snout and lower jaw, fewer predorsal scales, and a moderately emarginate caudal fin. *S. leiurus* exhibits a deeper body profile, higher predorsal scale and anal fin ray counts, and lacks caudal pigmentation, setting it apart from its congeners. *S. strongylura* is morphologically robust, with a shorter snout, fewer vertebrae and predorsal scales, and a rounded or truncated caudal fin with dark posterior margins. Pairwise genetic distances (K2P) ranging from 17.8 to 23.7% among the three species of *Strongylura* clearly support the distinctiveness and exceed typical COI divergence thresholds for teleosts. Comparative analysis with previously described species from other ocean basins further highlights these distinctions, reinforcing the reliability of combined morphological and molecular approaches. This study enhances the taxonomic resolution within *Strongylura* in Indian waters and provides a baseline for future biodiversity and fisheries assessments of the group.

Keywords: *Needlefishes, otolith, morphometric analysis, COI, phylogenetic analysis*

Introduction

The genus *Strongylura* van Hasselt, 1824 (Belonidae), comprising elongated, surface-dwelling needlefishes, is widely distributed across tropical and subtropical marine and estuarine environments worldwide (Collette, 1999; 2022). Members of the genus are characterised by a caudal fin rounded or truncated; no keels on the caudal peduncle; no posterior black dorsal-fin lobe at any size; dorsal-fin rays 12 to 21 (Collette and Carpenter, 2003; Collette, 1999). The group exhibits considerable morphological conservatism, often leading to difficulties in species delimitation based solely on external features (Lovejoy, 2000). Globally, *Strongylura* comprises approximately 15 valid species (Lovejoy, 2000; Fricke *et al.*, 2025; Froese and Pauly, 2024). Species of the genus *Strongylura* show a broad global distribution, with several species occurring exclusively in the Atlantic Ocean, such as *S. forsythia*, *S. notata*, *S. marina*, *S. timucu,* and *S. senegalensis,* which are primarily restricted to coastal and estuarine habitats of the western and eastern Atlantic (Collette and Carpenter, 2003). In contrast, the Indo-Pacific and Indian Ocean regions host a diverse assemblage including *S. incisa*, *S. leiurus*, *S. strongylura*, *S. krefftii*, *S. anastomella*, and *S. urvillii*, inhabiting coastal lagoons, mangroves, reef flats, and brackish or freshwater systems from East Africa and the Persian Gulf to the western Pacific. Three of these–*S. incisa*, *S. leiurus*, and *S. strongylura*- are currently documented from Indian waters (Fricke *et al.*, 2025; Froese and Pauly, 2024; Roul *et al.*, 2018, 2019).

Despite their apparent similarity, molecular phylogenetic studies have revealed that *Strongylura* is polyphyletic, with multiple independent lineages emerging within the genus (Banford *et al.*, 2004; Lovejoy *et al.*, 2004). This underlines the necessity for integrative taxonomic approaches to reassess species boundaries and phylogenetic relationships within the genus. Species of the genus *Strongylura* are of minor commercial importance globally, but are regularly caught in gillnets, hook-and-line, and seine nets (Collette and Carpenter, 2003; Sabrah *et al*., 2018; Toji *et al*., 2024). They are typically marketed fresh, frozen, or smoked and consumed locally despite the green colouration of their bones, with the flesh generally considered palatable (Collette, 1984; Collette and Carpenter, 2003). In India, species of *Strongylura* contribute to small-scale pelagic fisheries and are commonly landed across both coasts and island ecosystems, including riverine and estuarine environments (Toji *et al*., 2024). While *S. incisa* is reef-associated and restricted to the southeast coast, species such as *S. leiurus* and *S. strongylura* are widely distributed, occurring in marine, brackish, and freshwater habitats, enhancing their availability to local fisheries (Toji *et al*., 2024). Despite their low economic value in large-scale commercial markets, their widespread presence and accessibility make them a vital part of local coastal livelihoods and a secondary resource in tropical pelagic fisheries (Collette and Carpenter, 2003; Banford *et al*., 2004; Toji *et al*., 2024).

The taxonomy of the genus *Strongylura* has historically been based primarily on morphological traits, with early revisions recognising a wide range of marine and freshwater species distributed across tropical and subtropical regions (Collette *et al*., 1984). Although these classical studies provided foundational descriptions, they were largely constrained by the limited meristic characters and lacked comprehensive taxonomic revision (Collette, 1974). Subsequent studies on *Strongylura* from Indian waters have also been restricted to a narrow set of morphological characteristics, without incorporating molecular evidence (Roul *et al*., 2018). As a result, several species complexes, particularly within the Indo-Pacific region, remain poorly resolved, highlighting the need for detailed and integrative taxonomic assessments (Lovejoy and Collette, 2001; Banford *et al*., 2004; Choi *et al*., 2016). In this context, a comprehensive reassessment of *Strongylura* from Indian waters is essential to establish a reliable taxonomic framework for future studies. The present study represents a baseline effort to confirm species identities in the region using an integrative taxonomic approach. By combining morphometric, meristic, otolith morphology, and molecular (COI) analyses, this study aims to resolve species boundaries within the genus *Strongylura*, detect potential cryptic diversity, and provide a more accurate understanding of species distribution along the Indian coast.

Material and methods

Specimen collection and identification

Specimens were collected from various locations along the east and west coasts of India, as well as the Andaman and Nicobar Islands and Lakshadweep Islands (Fig. 1), between 2021 and 2023, as part of a systematic survey of belonid fishes (Table 1). Samples were obtained from local fish landing centres where fishermen employed gillnets in shallow coastal waters (0-5 m depth). The specimens were immediately collected after capture and transported to the laboratory following preliminary identification (Thomas *et al*., 2025) and photographic documentation. Tissue samples were preserved in 95% ethanol for molecular analysis.

Table 1. Geographic locations of specimen collection during the current study

No.	Species	Co-ordinate	Collection location
1	*Strongylura incisa* (N=9)	8°53′19.5″N 78°10′23.1″E	Tharuvaikulam, Tuticorin, Tamil Nadu
2	*Strongylura incisa* (N=3)	11°39′33.2″N 92°43′33.6″E	Junghalighat jetty, Sri Vijaya Puram, A& N Islands
3	*Strongylura incisa* (N=3)	16°57′26.4″N 82°16′09.2″E	Kakinada Port Landing Centre, Kakinada, Andhra Pradesh
4	*Strongylura leiurus* (N=5)	9°58′57.3″N 76°14′33.9″E	Kalamukk, Kochi, Kerala
5	*Strongylura leiurus* (N=2)	12°51′36.7″N, 74°49′55.3″E	Dhake, Mangalore, Karnataka
6	*Strongylura leiurus* (N=3)	20°54′07.9″N 70°21′52.4″E	Light house, Veraval, Gujarat
7	*Strongylura leiurus* (N=3)	19°58′48.0″N 86°19′12.0″E	Nuagarh, Astaranga, Odisha
8	*Strongylura leiurus* (N=2)	9°16′50.6″N 79°12′27.3″E	Pamban, Mandapam, Tamil Nadu
9	*Strongylura strongylura* (N=4)	11°39′33.2″N 92°43′33.6″E	Junghalighat jetty, Sri Vijaya Puram, A&N Islands
10	*Strongylura strongylura* (N=3)	19°01′12.6″N 72°49′04.2″E	Worli, Mumbai, Maharashtra
11	*Strongylura strongylura* (N=5)	17°41′44.8″N 83°18′08.8″E	Kavaratti jetty, Kavaratti, Lakshadweep
12	*Strongylura strongylura* (N=3)	10°33′59.1″N 72°38′13.6″E	Jalaripetta, Vishakhapatnam, Andhra Pradesh

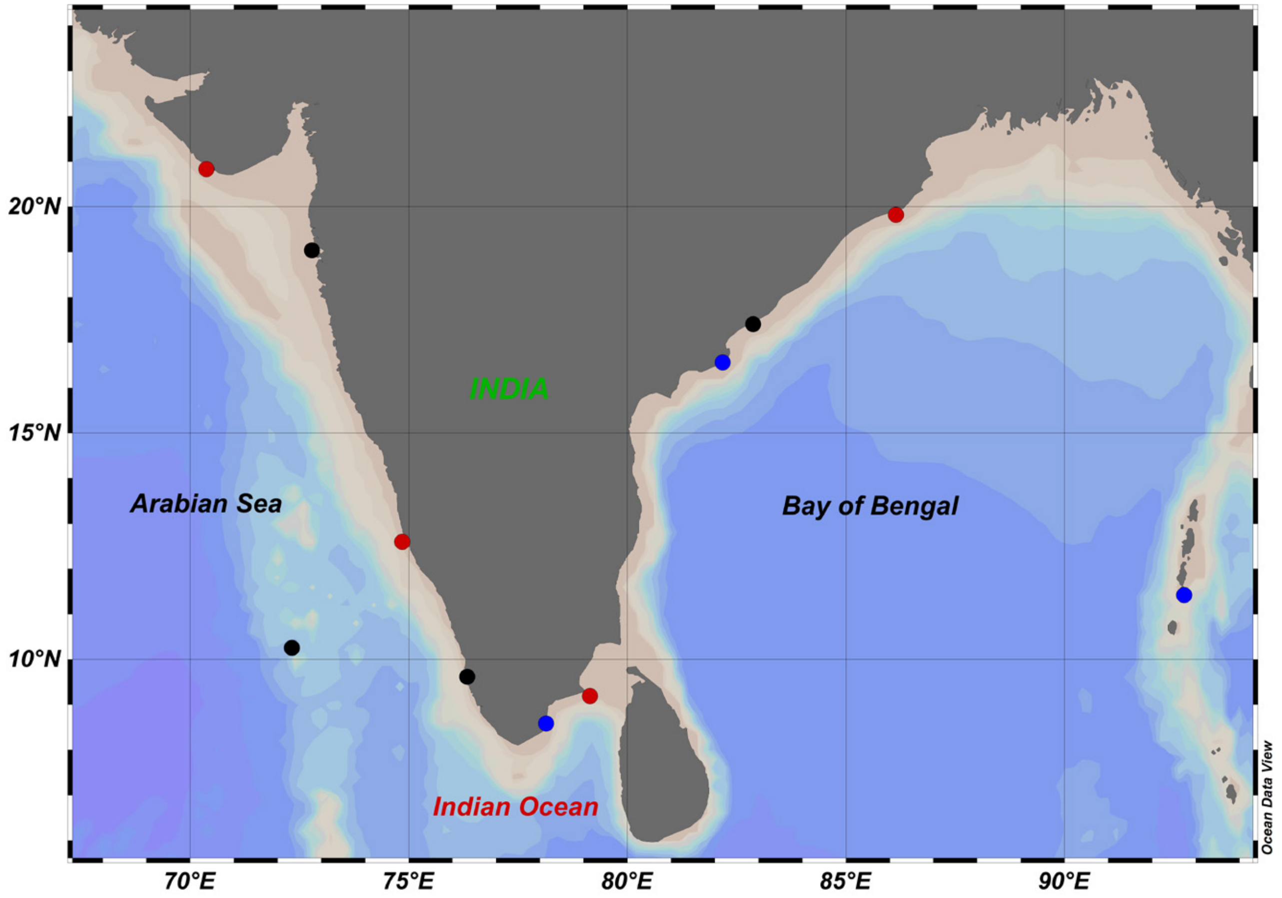

Fig. 1. Map showing the occurrence points of materials examined during the present study (*S. incisa* – blue dots; *S. leiurus* – red dots; *S. strongylura* – black dots)

Morphometric and meristic analysis

Morphological characters, including body colouration, morphometric measurements, and meristic counts, were recorded for all specimens. Measurements were made following standard protocols as described by Collette (1984) and Yankova *et al.* (2023), and identification was confirmed using diagnostic features outlined by Collette and Su (1986). All measurements were taken using vernier callipers with 0.1 mm precision and expressed as percentages of standard length (SL) or head length (HL) following Hubbs and Lagler (1958). A total of 27 morphometric measurements and 7 meristic counts were recorded. Morphometric and meristic data were compared with previously published descriptions (Collette, 1984; Collette, 2003). Details of type specimens and associated museum reference materials examined in this study are provided, and the status of specimens used in previous studies (*e.g.*, FAO, 1983; Roul *et al.*, 2018) is clarified with respect to their designation as type or non-type reference material. Vertebral counts were obtained from X-ray radiographs, following the methodology of Jawad and Jig (2017). Sagittal otoliths were extracted in accordance with Abdussamad (2015) and photographed under high-resolution digital imaging for shape comparison. All identified specimens were preserved and deposited in the Marine Biodiversity Museum at the Central Marine Fisheries Research Institute (CMFRI), Kochi, Kerala, and specimens were given Designated National Repository (DNR) numbers.

Molecular analysis

Total genomic DNA was extracted from ethanol-preserved tissue samples using a commercial DNA extraction kit (Origin), adhering to the manufacturer's protocol. DNA quality and concentration were assessed using a Nanodrop spectrophotometer (Eppendorf). The mitochondrial gene region, cytochrome c oxidase subunit I (COI) (Hebert *et al.*, 2003) was amplified via polymerase chain reaction (PCR) using the primer WARD 1 (Ward *et al.*, 2005). Each PCR reaction was performed in a 25 µl volume comprising 50 ng of template DNA, 3 mM $MgCl_2$, and 0.3 mM of each primer. The thermal cycling profile included an initial denaturation at 94 °C for 3 min, followed by 30 cycles of denaturation at 94 °C for 30 s, annealing at 50 °C for 30 s, and extension at 72 °C for 1 min, with a final extension step of 7 min at 72 °C. The amplified products were visualised on 1.2% agarose gels stained with ethidium bromide.

Post-PCR, sequencing was performed by Genspec, Cochin, India. Sequence quality was assessed using Sequence Scanner v1.0 (Applied Biosystems, 2010). Multiple sequence alignments were conducted using Clustal W (Thompson *et al.*, 2003). Comparative molecular analyses were conducted using reference sequences retrieved from GenBank (Benson *et al.*, 2013) and the Barcode of Life Data Systems (BOLD) (Ratnasingham and Hebert, 2007). These sequences were aligned with newly generated sequences using the Clustal W algorithm in BIO Edit (Hall *et al.*, 1999). Details of published sequences used for alignment are summarised in Table 5. Phylogenetic analysis was performed to determine genetic distances between the sequences using the Maximum Likelihood (ML) method based on the Kimura-2-parameter or K2P (Kimura, 1980) in MEGA 11 (Tamura *et al.*, 2021). with 1000 bootstrap replications (Felsenstein, 1985). Mean pairwise genetic distances were calculated using the K2P model (Kimura, 1980). The sequences were submitted to the NCBI GenBank, and accession numbers were obtained (Table 1).

Results

A total of 45 specimens belonging to the genus *Strongylura* were collected as part of this taxonomic investigation. Based on detailed morphological, meristic, otolith, and molecular analyses, these specimens were identified as *Strongylura incisa* (Valenciennes, 1846), *Strongylura leiurus* (Bleeker, 1850), and *Strongylura strongylura* (van Hasselt, 1823).

Systematics

Order: Beloniformes
Family: Belonidae Bonaparte, 1835
Genus: *Strongylura* van Hasselt, 1824

Strongylura incisa Valenciennes, 1846 (Fig. 2a)

Common name: Reef needlefish

Type specimen: *Belone incisa* Valenciennes in Cuvier & Valenciennes 1846, Indian Ocean. Holotype (unique)

Synonyms: *Belone incisa* Valenciennes, 1846; *Belone leiuroides* Bleeker, 1851; *Belone liuroides* Günther, 1866; *Rhaphiobelone robusta* Schultz, 1953; *Tylosurus terebra* Whitley, 1927

Materials examined: The materials examined were from 15 specimens. DNR No: GB 10.2.8.6.1 (437-462mm SL), Collected by Gillnet operation, From Tuticorin (8°53′19.5″N 78°10′23.1″ E), Sri Vijaya Puram (11°39′33.2″N 92°43′33.6″ E), and Kakinada (16°57′26.4″N 82°16′09.2″ E), depth 0-5 m; collected by Toji Thomas, on the period of 2021-2023.

Diagnosis: *Strongylura incisa* can be distinguished from its congeners by a combination of morphological and meristic characters. It possesses a relatively long head and a relatively elongated predorsal region. The dorsal fin typically has 18-19 rays. and the anal fin has 21-22 rays. The dorsal and anal fin origins are closely aligned, with the dorsal fin origin typically between the 4th and 5th anal fin rays. The caudal fin is described as slightly forked or emarginate. This species lacks prominent spots or bars on the body, though it may exhibit a mark on the cheek. Scales are absent at the anal fin and dorsal fin base.

Description: *Strongylura incisa* is characterised by a slender, elongate body with a body depth at the level of the anal fin ranging from 3.9-4.1% of standard length (SL). The head is relatively large, with a head length (HL) measuring 16-17.8 cm, accounting for 36.6-38.5% of SL. The eyes are prominent (Fig. 2b), with an eye diameter of 4.0-4.2% of HL, and the interorbital

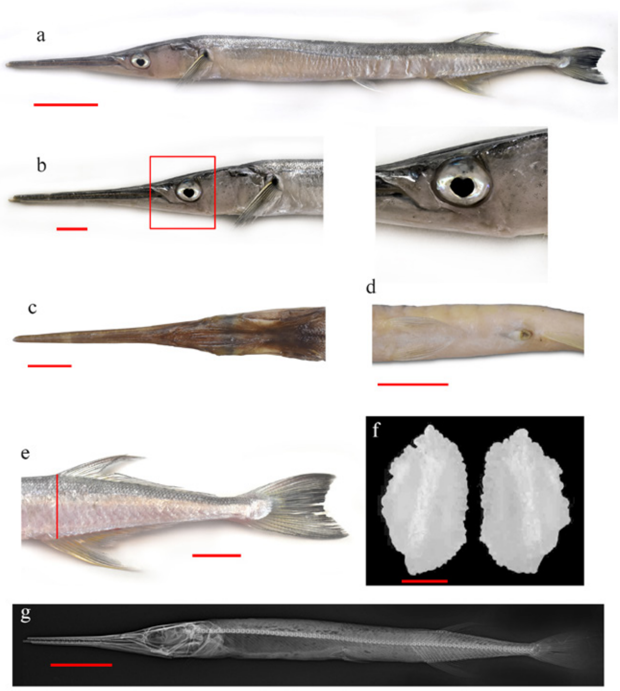

Fig. 2. Morphological and anatomical characteristics of *Strongylura incisa* (DNR No. GB 10.2.8.6.1, SL- 446 mm) (a) Lateral view (Scale bar = 5 cm) (b) Head with pectoral fin (Scale bar = 2 cm) (c) Upper head (Scale bar = 2 cm) (d) Pelvic–Anal (Scale bar = 2 cm) (e) Dorsal, anal and caudal fin shape (Scale bar = 2 cm) (f) Sagittal otolith (Scale bar = 1mm), and (g) Vertebrae (Scale bar = 5 cm)

width ranges from 4.4-4.6% of HL. Cranial proportions include lower jaw and preorbital lengths of 24.6-26.2% and 24.2-26.1% of HL, respectively, and a snout length of 24.7-27% of HL. Head width and head depth measure 5.7-6.1% and 3.8-4.0% of HL, respectively (Fig. 2c). Proportional distances relative to SL include pre-pectoral length (38.4-40.7%), predorsal length (78.7-80.3%), and preanal length (76.7-78.3%). The distance between the origins of the dorsal and anal fins is short, ranging from 1.8-2.0% of SL (Fig. 2e). The dorsal and anal fin base lengths measure 14.8-14.9% and 15.8-16.1% of SL, respectively. Pectoral and pelvic fin lengths are 10.2-10.5% and 6.9-7.1% of SL (Fig. 2d). Fin heights include dorsal height (10.8-11.2%) and anal height (9.3-9.6%) of SL. Body widths include caudal peduncle width (1.3-1.4%), caudal peduncle depth (2.3-2.5%), width at the pelvic fin (5.6-5.8%), depth at the pelvic fin (4.75-4.9%), and width at the anal fin (5.8-6.0% of SL). The dorsal fin comprises 18-19 rays, the anal fin 21-22 rays, and the pectoral fin 10-11 rays. The pelvic fin consistently comprises 6 rays. The predorsal scale count ranges from 120 to 128, and the vertebral count ranges from 74 to 76. The caudal fin is slightly forked or emarginate (Fig. 2e). All morphometric and meristic data are presented in Tables 2 and 3.

Table 2. Detailed morphometric and meristic characteristics of the genus *Strongylura,* available along the Indian coast (Present study)

No.	Characters	*Strongylura incisa* (N=15)				*Strongylura leiurus* (N=15)				*Strongylura strongylura* (N=15)			
		Range	AVG	S. D	S. E	Range	AVG	S. D	S. E	Range	AVG	S. D	S. E
1	Total length (cm)	48-50.3	49.13	1.15	0.66	37.1-52.7	45.1	5.01	1.77	28.1-39.2	34.42	4.48	2
2	Standard length (cm)	43.7-46.2	44.83	1.27	0.73	34.3-48	41.29	4.46	1.58	25.4-35.8	31.06	4.12	1.84
3	Head length (cm)	16-17.8	16.8	0.92	0.53	11.8-15.3	13.58	1.10	0.39	9.5-13.1	11.38	1.36	0.61
A	In % of SL												
1	Head length	36.6-38.5	37.45	0.98	0.57	32-36	32.98	1.43	0.54	35.7-37.6	36.70	0.79	0.35
2	Pre-pectoral length	38.4-40.7	39.23	1.26	0.73	33-37	35.04	1.34	0.51	37-40	38.45	1.10	0.49
3	Predorsal length	78.7-80.3	79.69	0.85	0.49	79.2-81	79.95	0.52	0.20	81.3-83.6	82.70	1.21	0.54
4	Preanal length	76.7-78.3	77.61	0.84	0.49	75-77	75.84	0.71	0.27	78.5-80.3	79.19	0.75	0.34
5	Distance b/w AF org-DF org	1.8-2	1.86	0.08	0.05	3.4-4.7	3.90	0.42	0.16	2.9-4.3	3.50	0.56	0.25
6	Dorsal baselength	14.8-14.9	14.87	0.07	0.04	13.5-14.8	14.09	0.43	0.16	10.2-12	10.76	0.75	0.34
7	Anal baselength	15.8-16.1	15.99	0.17	0.10	15.7-17.9	17.15	0.62	0.23	11.8-13.8	12.62	0.77	0.34
8	Pectoral length	10.2-10.5	10.41	0.21	0.12	7-8.4	7.84	0.40	0.15	5.6-9.4	8.31	1.60	0.72
9	Pelvic length	6.9-7.1	7.03	0.07	0.04	5.1-5.75	5.46	0.22	0.08	5.2-5.9	5.48	0.30	0.14
10	Dorsal height	10.8-11.2	11.01	0.20	0.11	5.7-7	6.43	0.43	0.16	8-9.8	8.56	0.73	0.33
11	Anal height	9.3-9.6	9.44	0.17	0.10	7.9-9.5	8.64	0.51	0.19	10.3-11.8	10.74	0.63	0.28
12	Caudal peduncle width	1.3-1.4	1.38	0.03	0.02	.8-1.1	0.96	0.10	0.04	.73-.86	0.81	0.05	0.02
13	Caudal peduncle depth	2.3-2.5	2.38	0.09	0.05	1.7-2.3	2.11	0.17	0.06	2.95-3.7	3.34	0.30	0.14
14	Width at pelvic	5.6-5.8	5.73	0.10	0.06	3.3-4.1	3.58	0.29	0.11	4.9-5.8	5.31	0.36	0.16
15	Depth at pelvic	4.75-4.9	4.87	0.09	0.06	4.4-5.4	4.75	0.28	0.11	5.5-7.1	6.37	0.58	0.26
16	Width at anal	5.8-6	5.87	0.07	0.04	2.8-3.2	3.02	0.14	0.05	3.4-3.8	3.62	0.18	0.08
17	Depth at anal	3.9-4.1	3.98	0.08	0.04	4.4-5.8	4.98	0.42	0.16	4.7-6.4	5.51	0.65	0.29
B	In % of HL												
1	Snout length	24.7-27	25.55	1.13	0.65	20.8-24	21.98	1.10	0.41	22.9-24.8	23.88	0.77	0.34
2	Head width	5.7-6.1	5.95	0.19	0.11	2.9-4.5	3.72	0.44	0.17	3-3.9	3.40	0.32	0.14
3	Head depth	3.8-4	3.94	0.14	0.08	4.4-5.7	4.90	0.42	0.16	5.3-6.4	5.80	0.41	0.19
4	Eye diameter	4-4.2	4.05	0.06	0.03	2.6-3.3	2.89	0.17	0.06	2.8-3.4	3.16	0.22	0.09
5	Interorbital width	4.4-4.6	4.50	0.07	0.04	2.9-3.7	3.21	0.24	0.09	2.7-3.4	2.91	0.26	0.11
6	Lower jaw length	24.6-26.2	25.19	0.87	0.50	21.4-26	23.18	1.39	0.53	24.2-25.7	25.06	0.64	0.28
7	Preorbital length	24.2-26.1	25.15	0.91	0.53	20.6-23.2	21.81	0.92	0.35	23-26.5	24.50	1.36	0.61
8	Postorbital length	7.5-8.6	8.06	0.50	0.29	7.3-8.2	7.75	0.27	0.10	9.1-10.3	9.62	0.44	0.20

Colouration: The body is predominantly silvery with a faint greenish sheen along the dorsal surface (Fig. 2). Fins are largely hyaline, while the caudal fin is distinctively edged in dark pigment.

Otolith morphology: The sagittal otolith of *Strongylura incisa* has an overall oval shape. The anterior and posterior ends are slightly pointed, giving it an elongated appearance. The dorsal and ventral margins are somewhat rounded. The surface texture appears granular with concentric growth rings.

Meristic formula: DF 18-19, AF 21-22, Pect F 10 - 11, Predorsal scales 120-128, Vertebrae 74-76

Distribution: Present investigations indicated their distribution along Tuticorin (Tamil Nadu), Kakinada (Andhra Pradesh), and the Andaman Islands (Bay of Bengal) (Fig. 1).

Remarks: *Strongylura incisa* (Valenciennes, 1846) was originally described from the Indian Ocean and is commonly recorded from Southeast Asia, including the Philippines (Lovejoy, 2000; Lovejoy *et al*., 2004; Astakhov, 2023). The species is currently treated as a valid member of the genus and has appeared in molecular phylogenetic studies as a distinct lineage (Banford *et al*., 2004). In India, reports of *S. incisa* are relatively recent and have primarily been based on morphological identification, with limited molecular confirmation (Roul *et al*., 2019). Indian records indicate the presence of the species along the southeast coast, though its distribution remains poorly understood due to the historical taxonomic ambiguity within the genus.

Strongylura leiurus Bleeker, 1850 (Fig.3a)

Common name: Banded needlefish

Type specimen: *Belone leiurus* Bleeker, 1850, Jakarta, Java, Indonesia. Syntypes: BMNH 1866.5.2.4, RMNH 6946

Synonyms: *Belone ciconia* Richardson, 1846; *Belone ferox* Günther, 1866; *Belone leira* Bleeker, 1850; *Belone leiurus* Bleeker, 1850; *Belone natalensis* Günther, 1866; *Belone tenuirostris* Blyth, 1858; *Rhaphiobelone dammermani* Fowler, 1934; *Strongylura leiurus leiurus* (Bleeker, 1850); *Strongylura leiyra* (Bleeker, 1850); *Strongylurus leiurus* (Bleeker, 1850); *Tylosurus leiurus* (Bleeker, 1850)

Materials examined: (N=15): DNR No: GB 10.2.8.7.1 (343- 480 mm SL), Collected by Gillnet operation, From; Mangalore (12°51′36.76″N, 74° 49′ 55.38″ E), Astaranga (19°58′48.0″N 86°19′12.0″ E), Mandapam (9°16′50.6″N 79°12′27.3″ E) Kochi (9°58′57.3″N 76°14′33.9″ E), Veraval (20°54′07.9″N 70°21′52.4″ E), depth 0-5 m; collected by Toji Thomas, on the period of 2021-2023

Diagnosis: *Strongylura leiurus* is differentiated by its relatively short head and a greater distance between the dorsal and anal fin origins, with the dorsal fin origin typically between the 7th-8th anal fin rays. The dorsal fin has 19-20 rays and the anal fin 23-24 rays. The caudal fin is emarginate. While lacking spots or bars on the main body, it exhibits spots on the anterior part of the body. Scales are present at the anal fin and dorsal fin base.

Description: *Strongylura leiurus* is distinguished by an elongated, slender body, with body depth at the anal fin ranging from 4.4-5.8% of standard length (SL). The head length varies from 11.8-15.3 cm, comprising 32.0-36.0% of SL. The eyes are well-developed (Fig. 3b), with an eye diameter of 2.6-3.3% of head length (HL), and an interorbital width of 2.9-3.7% of HL. The lower jaw measures 21.4-26.0% of HL, while preorbital and snout lengths range from 20.6-23.2% and 20.8-24.0% of HL, respectively. Head width and depth range from 2.9-4.5% and 4.4-5.7% of HL, respectively (Fig. 3c). Measurements relative to SL include pre-pectoral length (33.0-37.0%), predorsal length (79.2-81.0%), and preanal length (75.0-77.0%). The distance between the origins of the anal and dorsal fins ranges from 3.4-4.7% of SL (Fig. 3e). Dorsal and anal base lengths are 13.5-14.8% and 15.7-17.9% of SL, respectively. The pectoral and pelvic fin lengths are 7.0-8.4%

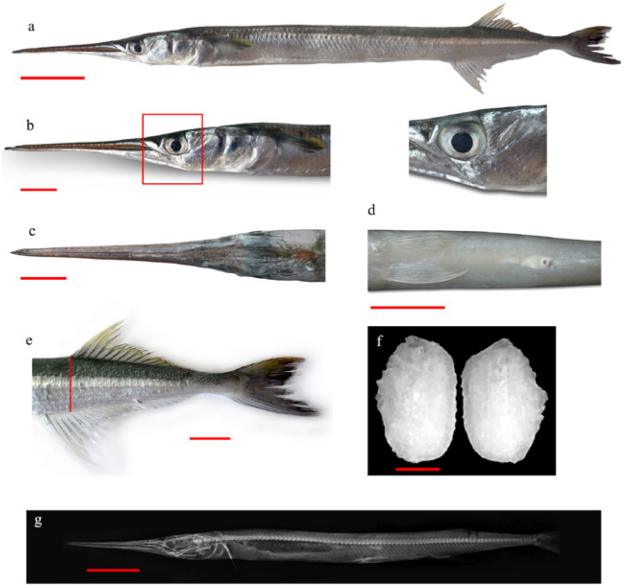

Fig. 3. Morphological and anatomical characteristics of *Strongylura leiurus* (DNR No. GB.10.2.8.7.1, SL- 341 mm) (a) Lateral view (Scale bar = 5 cm) (b) Head with pectoral fin (Scale bar = 2 cm) (c) upper head (Scale bar = 2 cm) (d) Pelvic–Anal (Scale bar = 2 cm) (e) dorsal, anal and caudal fin shape (Scale bar = 2 cm) (f) otolith (Scale bar = 1 mm) , and (g) vertebrae (Scale bar = 5 cm)

and 5.1-5.75% of SL, respectively (Fig. 3d). Fin heights include dorsal height (5.7-7.0%) and anal height (7.9-9.5%) of SL. The caudal peduncle width and depth vary from 0.8-1.1% and 1.7-2.3% of SL, respectively. Width and depth at the pelvic fin measure 3.3-4.1% and 4.4-5.4%, respectively, while the width at the anal fin ranges from 2.8-3.2% of SL. The dorsal fin consists of 19-20 rays, the anal fin of 23-24 rays, and the pectoral fin of 11-12 rays. The pelvic fin consistently bears 6 rays. The predorsal scale count ranges from 169 to 188, and the vertebral count varies from 83 to 85. The caudal fin is emarginate in shape (Fig. 3e). All morphometric and meristic data are summarised in Tables 2 and 3.

Colouration: The body displays a bright silver tone, subtly tinged with green dorsally (Fig. 3). All fins are hyaline, with the caudal fin bearing a thin dark margin.

Otolith morphology: The sagittal otolith of *Strongylura leiurus* is more rounded and less elongated compared to the other two species. It has a more symmetrical, blunt oval shape. The margins, especially the dorsal and ventral sides, are smooth and curved. The overall shape is compact and robust.

Meristic formula: DF 19-20, AF 23-24, Pect F 11 - 12, Predorsal scales 169-188, Vertebrae 83-85.

Distribution: Present records confirm its occurrence along Kerala, Karnataka, and Gujarat (Arabian Sea), as well as Tamil Nadu and Odisha (Bay of Bengal) (Fig.1).

Remarks: *Strongylura leiurus* (Bleeker, 1850) is one of the more widely reported species in the Indo-West Pacific, ranging from the Indian subcontinent to northern Australia (Lovejoy, 2000; Lovejoy *et al.*, 2004; Al-Salim and Ali, 2007). In Indian waters, it has been recorded from both the southwest and east coasts (Aneesh *et al.*, 2013; Roul *et al.*, 2018; Roul *et al.*, 2019; Sheikh *et al.*, 2022). The species has historically been confused with its congeners, especially due to overlapping meristic traits. However, molecular studies have consistently identified *S. leiurus* as a distinct clade, often grouped with *S. incisa* and *S. strongylura* in Indo-Pacific phylogenies (Lovejoy *et al.*, 2004).

Strongylura strongylura van Hasselt, 1823 (Fig. 4a)

Common name: Spottail needlefish

Type specimen: *Belone strongylura*, van Hasselt, 1823:Vizagapatam, India. Holotype (unique): whereabouts unknown.

Synonyms: *Belone caudimacula* Cuvier, 1829; *Belone oculata* Leschenault, 1846; *Belone saigonensis* Sauvage, 1879; *Belone strongylura* van Hasselt, 1823; *Belone strongylurus* van Hasselt, 1823; *Strongylura caudimaculata* van Hasselt, 1824; *Strongylura strongylurus* (van Hasselt, 1823); *Strongylurus strongylura* (van Hasselt, 1823); *Tylosurus strongilurus* (van Hasselt, 1823); *Tylosurus strongylorus* (van Hasselt, 1823); *Tylosurus strongylura* (van Hasselt, 1823); *Tylosurus strongylurus* (van Hasselt, 1823)

Materials examined (N=15): DNR No: GB 10.2.8.8.1 (254-358 mm SL) Collected by Gillnet operation, From: Vizag (17°41'44.8"N 83°18'08.8" E), Kavaratti (10°33'59.1"N 72°38'13.6" E), Sri Vijaya Puram (11°39'33.2"N 92°43'33.6" E), Bombay (19°01'12.6"N 72°49'04.2" E), depth 0-5 m; collected by Toji Thomas, on the period of 2021-2023

Table 3. Summary of important morphometric and meristic characters of species of *Strongylura* collected during the present study in comparison with previous records

Sl. no	Characters	*Strongylura incisa*			*Strongylura leiurus*			*Strongylura strongylura*		
		FAO (1983)	Roul *et al.* 2018	Present study	FAO (1983)	Roul *et al.*, 2018	Present study	FAO (1983)	Roul *et al.* 2018	Present study
1	Dorsal fin rays	11 - 20	19-20	18-19	17- 21	18-21	19-20	12 - 15	12 - 15	13-14
2	Anal fin rays	21-25	21-23	21-22	23-25	21-26	23-24	15-18	16- 18	17-18
3	DF- AF origin	4th- 6th	4th -5th	4th-5th	7th-10th	7th-9th	7th-8th		6th- 7th	5th-7th
4	Pectoral rays		12	10 - 11	10 - 11	10 - 12	11 - 12	10 - 12	9 - 12	10 - 11
5	Predorsal scales	100-120	100-125	120-128	130-160	130-180	169-188	100-130	97-123	115-136
6	Vertebrae			74-76			83-85	59-65		61-63
7	Caudal fin shape		Emarginate	Slightly forked or Emarginate	Emarginate	Emarginate	Emarginate	Truncate or Rounded	Rounded or Truncate	Rounded or Truncate
8	Spots or bars	Absent	Cheek	Cheek	Absent	Anterior part of body	Anterior part of body	Spot in caudal peduncle	Spot in caudal peduncle	Spot in caudal peduncle
9	Scales in AF- DF base	Absent	Absent	Absent	Present	Absent	Present	Present	Present	Present

Diagnosis: *Strongylura strongylura* is characterised by its relatively short total length and head length. The dorsal fin has 13-14 rays and the anal fin 17-18 rays. The dorsal fin origin is typically between the 5th and 7th anal fin rays. A distinct spot is present on the caudal fin. The caudal fin is rounded or truncated. Scales are present at the anal fin and dorsal fin base.

Description: *Strongylura strongylura* is a slender, elongate species, with body depth at the level of the anal fin ranging from 4.7-6.4% of standard length (SL). Head length varies from 9.5-13.1 cm, constituting 35.7-37.6% of SL. The eyes are distinct and moderately large (Fig. 4b), with diameters of 2.8-3.4% of head length (HL), and interorbital width ranges from 2.7-3.4% of HL. The lower jaw length is 24.2-25.7% of HL, while preorbital length ranges from 23.0-26.5% and snout length from 22.9-24.8% of HL. Head width and depth range from 3.0-3.9% and 5.3-6.4% of HL, respectively (Fig. 4c). Proportional measurements relative to SL include pre-pectoral length (37.0-40.0%), predorsal length (81.3-83.6%), and preanal length (78.5-80.3%). The distance between the origins of the anal and dorsal fins measures 2.9-4.3% of SL (Fig. 4e). Dorsal and anal base lengths measure 10.2-12.0% and 11.8-13.8% of SL, respectively. Pectoral and pelvic fin lengths range from 5.6-9.4% and 5.2-5.9% of SL, respectively (Fig. 4d). Dorsal and anal heights range from 8.0-9.8% and 10.3-11.8% of SL, respectively. The caudal peduncle is narrow, with a width ranging from 0.73-0.86% and depth from 2.95-3.7% of SL. Width and depth at the pelvic fin range from 4.9-5.8% and 5.5-7.1% of SL, respectively, while the width at the anal fin ranges from 3.4-3.8% of SL. The dorsal fin comprises 13-14 rays, the anal fin 17-18 rays, and the pectoral fin 10-11 rays. The pelvic fin consists of 6 rays. Predorsal scales range from 115 to 136, and the vertebral count is between 61 and 63. The caudal fin is either rounded or truncated in shape (Fig. 4e). All morphometric and meristic data are provided in Tables 2 and 3.

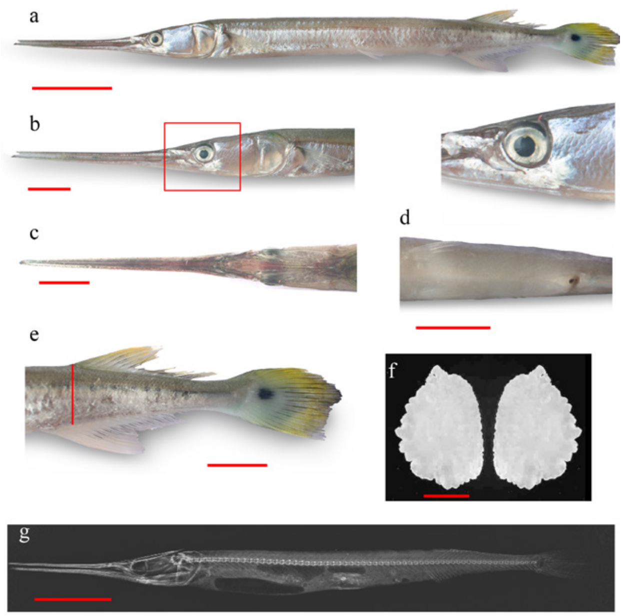

Fig. 4. Morphological and anatomical characteristics of *Strongylura strongylura* (DNR No. GB.10.2.8.8.1, SL- 358 mm) (a) Lateral view (Scale bar = 5 cm) (b) Head with pectoral fin (Scale bar = 2 cm) (c) upper head (Scale bar = 2 cm) (d) Pelvic–Anal (Scale bar = 2 cm) (e) dorsal, anal and caudal fin shape (Scale bar = 2 cm) (f) otolith (Scale bar = 1 mm) , and (g) vertebrae (Scale bar = 5 cm)

Colouration: This species has a bright silvery body with a slight green dorsal hue (Fig. 4). The fins are hyaline, though the caudal fin is notable for its dark edging. The caudal fin bears a distinct dark spot.

Otolith morphology: The sagittal otolith of *Strongylura strongylura* is similar to *S. incisa* in its elongated form but with distinctively serrated or jagged margins. The anterior and posterior ends are pointed, and the dorsal and ventral margins are notably irregular, with small projections. This gives the otolith a more pronounced, "toothed" or saw-like appearance along its edges.

Meristic formula: DF 18-19, AF 21-22, Pect F 10 - 11, Predorsal scales 120-128, Vertebrae 74-76

Distribution: Recorded from Maharashtra and Lakshadweep (Arabian Sea), and from Andhra Pradesh and the Andaman Islands (Bay of Bengal) (Fig. 1).

Remarks: *Strongylura strongylura* (van Hasselt, 1823), originally described from the east coast of India, has a confirmed distribution spanning the eastern Indian Ocean to the Western Central Pacific, including India, Sri Lanka, Southeast Asia, and northern Australia (Collette, 1984; Al-Salim and Ali, 2007). Within India, it is documented from the southwest coast (Rameshkumar *et al.*, 2014; Roul *et al.*, 2018; Roul *et al.*, 2019). Historically, this species has served as a reference point for comparison with closely related taxa and has been considered a representative of the genus in global taxonomic and phylogenetic studies (Banford *et al.*, 2004; Lovejoy, 2000).

Key to the genus Strongylura in Indian waters

Modified key adapted from Collette, 1999, and observations during the present study

1a. Body strongly laterally compressed or rounded; with or without vertical bars; Caudal fin distinctly forked; presence or absence of keels on caudal peduncle; presence of expanded black lobe in the posterior part of the dorsal fin; anal-fin rays 13 to 26; dorsal-fin rays 19 to 27, exclusively marine... ***Marine genera (Ablennes, and Tylosurus)***

1b. Body rounded; without vertical bars; caudal fin rounded or truncated; no keels on caudal peduncle; no posterior black dorsal-fin lobe at any size; anal-fin rays 13 to 23; dorsal-fin rays 12 to 21, seen in freshwater, marine, or brackish ...(2)

2a. Dorsal-fin rays 12 to 15; anal-fin rays 15 to 18; bases of dorsal and anal fins covered with scales, prominent black spot at base of caudal fin; predorsal scales 100 to 130 .... ***Strongylura strongylura***

2b. Dorsal-fin rays 17 to 21; anal-fin rays 21 to 27; bases of dorsal and anal fins without scales, no black spot at base of caudal fin .... (3)

3a. Predorsal scales 100 to 125; dorsal-fin origin over anal-fin rays 4 to 6; prominent, elongate spot on cheek between opercle and preopercle; pectoral fin with a yellowish tinge basally; dorsal and anal fin with yellowish rays with blackish tinge at the central region; caudal with yellowish tinge basally and greyish towards margin ....***Strongylura incisa***

3b. Predorsal scales 130 to 180; dorsal-fin origin over anal-fin rays 7 to 10; black bar on cheek between opercle and preopercle, and anterior part of the body; pectoral fins with a distal dark spot, tip of fins yellow in fresh specimens; tip of dorsal and anal-fin lobes yellowish, caudal fin dark with a yellowish tinge on upper lobe .... ***Strongylura leiurus***

Molecular analysis

A total of 14 sequences, including 3 newly generated and 11 retrieved from NCBI GenBank and BOLD, were used in this study (Table 5). Maximum likelihood (ML) phylogenetic analysis of COI sequences recovered three distinct clades corresponding to *Strongylura incisa*, *S. leiurus*, and *S. strongylura* (Fig. 5). Sequences generated in the present study, *S. strongylura* (PP833599), *S. leiurus* (PP833598), and *S. incisa* (PP833600) were grouped with conspecific sequences retrieved from GenBank and BOLD. The *S. strongylura* sequence (PP833599)

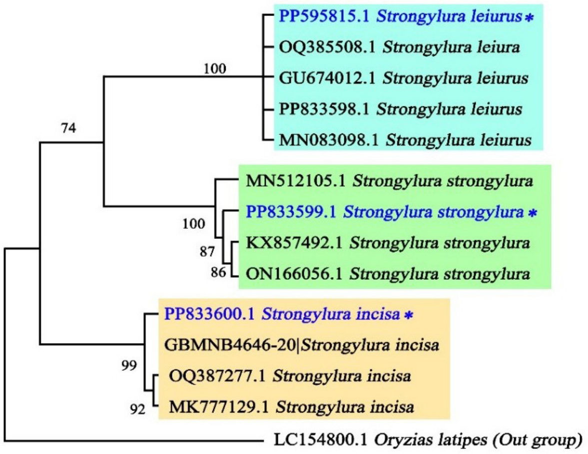

Fig. 5. Maximum Likelihood phylogenetic tree of the genus *Strongylura* using the mitochondrial COI gene

Table 4. Inter-species genetic distances table (K2P Table) based on COI sequences of genus *Strongylura*

	1	2	3	4	5	6	7	8	9	10	11	12	13
PP833599 *Strongylura strongylura*	0												
KX857492 *Strongylura strongylura*	0.004												
ON166056. *Strongylura strongylura*	0.004	0.000											
MN512105 *Strongylura strongylura*	0.006	0.010	0.010										
PP833598 *Strongylura leiurus*	0.181	0.180	0.180	0.184									
GU674012 *Strongylura leiurus*	0.181	0.180	0.180	0.184	0.000								
PP595815 *Strongylura leiurus*	0.181	0.180	0.180	0.184	0.000	0.000							
MN083098 *Strongylura leiurus*	0.184	0.183	0.183	0.187	0.002	0.002	0.002						
OQ385508 *Strongylura leiurus*	0.181	0.180	0.180	0.184	0.000	0.000	0.000	0.002					
PP833600 *Strongylura incisa*	0.182	0.185	0.185	0.178	0.237	0.237	0.237	0.242	0.238				
OQ387277 *Strongylura incisa*	0.181	0.184	0.184	0.178	0.245	0.245	0.245	0.249	0.245	0.004			
MK777129 *Strongylura incisa*	0.185	0.187	0.187	0.181	0.249	0.249	0.249	0.254	0.249	0.006	0.002		
GBMNB4646-20 *Strongylura incisa*	0.182	0.185	0.185	0.178	0.237	0.237	0.238	0.242	0.238	0.000	0.004	0.006	
LC154800 *Oryzias latipes*	0.307	0.307	0.307	0.298	0.322	0.322	0.322	0.318	0.322	0.270	0.275	0.279	0.270

Table 5. List of all comparative sequences (COI) for this study, retrieved from NCBI and BOLD used for phylogenetic tree construction

Sl. No	Species name	BOLD Accession number	NCBI Accession number	Collection location
1	*Strongylura strongylura*		PP833599	India
2	*Strongylura strongylura*	GBMIN121375-17	KX857492	India, Sundarbans
3	*Strongylura strongylura*	GBMNE85305-22	ON166056	Chilka lake, India
4	*Strongylura strongylura*	GBMNE36200-21	MN512105	Pakistan
5	*Strongylura leiurus*		PP833598	India
6	*Strongylura leiurus*	FOAJ581-09	GU674012	Indonesia
7	*Strongylura leiurus*	GBMNB8586-20	MN083098	Bangladesh
8	*Strongylura leiurus*	PHILA220-13	OQ385508	Philippines
9	*Strongylura leiurus*		PP595815	Pakistan
10	*Strongylura incisa*		PP833600	India
11	*Strongylura incisa*	PHIVS216-16	OQ387277	Philippines
12	*Strongylura incisa*	GBMNB7139-20	MK777129	Vietnam
13	*Strongylura incisa*	GBMNB4646-20	MH377852	India
14	*Oryzias latipes*		LC154800	Japan

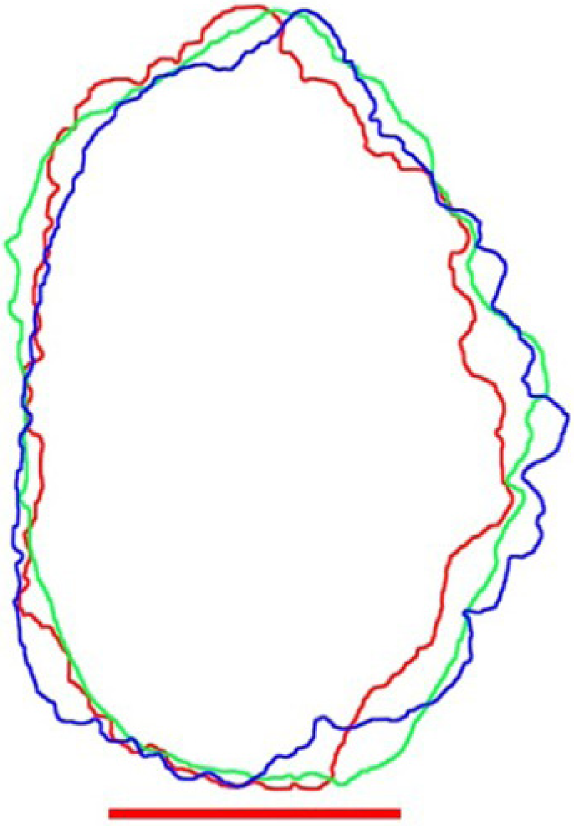

Fig. 6. Comparison of left sagittal otolith shape of genus *Strongylura*–*S. incisa* (green), *S. leiurus* (red), *S. strongylura* (blue) (Scale bar = 1 mm)

clustered with reference sequences KX857492 and ON166056 (India) and MN512105 (Pakistan). The *S. leiurus* sequences (PP833598) clustered with sequences from Pakistan (PP595815), Indonesia (GU674012), Bangladesh (MN083098), and the Philippines (OQ385508). Similarly, *S. incisa* (PP833600) was grouped with reference sequences from the Philippines (OQ387277) and Vietnam (MK777129). Each clade was consistently resolved with no overlap among the three species.

Pairwise genetic distances (K2P model) further supported species-level distinctiveness (Table 4). Minimum interspecific distances were 17.8% between *S. strongylura* and *S. incisa*, 18.0% between *S. strongylura* and *S. leiurus*, and 23.7% between *S. incisa* and *S. leiurus*. These values represent clear genetic gaps among the three taxa and align with species-level divergence thresholds commonly used in teleost COI barcoding studies.

Discussion

Integrated taxonomy has played a pivotal role in resolving species boundaries and revealing cryptic diversity in marine fishes globally (Hata *et al.*, 2022; Pante *et al.*, 2015; Zarei *et al.*, 2022), with similar successes reported from India in both freshwater and marine taxa, including the discovery of new species and resolution of species complexes (Laskar *et al.*, 2024; Singh *et al.*, 2022; Abdussamad *et al.*, 2022; 2023). Within Belonidae, recent integrative work has further refined species limits, highlighting its effectiveness (Toji *et al.*, 2024). Despite the ecological and commercial importance of *Strongylura* and the occurrence of its type species (*S. strongylura*) from Indian waters (van Hasselt, 1823), the genus remains taxonomically challenging due to morphological conservatism, overlapping meristic characters, and its reported polyphyletic nature (Mees, 1962; Collette, 1968; Lovejoy, 2000; Banford *et al.*, 2004; Lovejoy *et al.*, 2004). These issues have led to frequent misidentifications and unclear species boundaries, emphasising the need for an integrative approach. Accordingly, the present study employs combined morphological and molecular analyses to resolve taxonomic ambiguities and provide a comparative account of *S. incisa*, *S. leiurus*, and *S. strongylura* from Indian waters.

Of the 15 recognised species within the genus *Strongylura*, six are restricted to the Atlantic Ocean, including *S. marina*, *S. notata*, *S. forsythia*, *S. timucu*, *S. hubbsi*, and *S. senegalensis* (Collette, 1974). Among the remaining nine species, three species, *S. exilis*, *S. fluviatilis*, and *S. scapularis,* are confined to the eastern Pacific region (Collette, 1999). Of the rest, *Strongylura krefftii* is a strictly freshwater species endemic to freshwater systems of Oceania. *S. incisa*, *S. leiurus*, *S. strongylura*, *S. anastomella*, and *S. urvillii* are primarily distributed in the Indo-Pacific region and share several overlapping morphological traits. To confirm the identities of the three species examined in this study (*S. incisa*, *S. leiurus*, and *S. strongylura*), we compared key meristic and external characters with literature descriptions of the other two taxa (Collette, 1984, 1999; Masuda *et al.*, 1984; Roul *et al.*, 2018). The dorsal fin ray counts ranged from 18-19 in *S. incisa*, 19-20 in *S. leiurus*, and 13-14 in *S. strongylura*, whereas *S. anastomella* showed 17-21 rays and *S. urvillii* 12-15. Anal fin rays were counted as 21-22 in *S. incisa*, 23-24 in *S. leiurus*, 17-18 in *S. strongylura*, 21-25 in *S. anastomella*, and 15-18 in *S. urvillii*. The position of the dorsal-fin origin also varied, occurring between the 4th-5th anal fin rays in *S. incisa*, 7th-8th in *S. leiurus*, 5th-7th in *S. strongylura*, 8th-9th in *S. anastomella*, and 8th-9th in *S. urvillii*. The presence or absence of scales at the base of the dorsal and anal fins was consistent across species: *S. strongylura* and *S. urvillii* retained basal scales, while *S. incisa*, and *S. anastomella* lacked them (Collette, 1984, 1999; Masuda *et al.*, 1984; Roul *et al.*, 2018).

Further differences were observed in vertebral and predorsal scale counts. *S. incisa* exhibited 74-76 vertebrae and 120-128 predorsal scales; *S. leiurus* had 83-85 vertebrae and 169-188 predorsal scales (Collette, 1989; Roul *et al.*, 2018); *S. strongylura* showed 61-63 vertebrae and 115-136 predorsal scales (Collette, 1989; Roul *et al.*, 2018); *S. anastomella* was reported with intermediate values (Masuda *et al.*, 1984), and *S. urvillii* possessed 59-65 vertebrae with similarly low scale counts (Collette, 1983; 1999). Caudal fin morphology was also diagnostic: *S. incisa* and *S. leiurus* displayed emarginate to slightly forked caudal fins; *S. strongylura*, *S. anastomella*, and *S. urvillii* exhibited truncate to rounded caudal fins. Pigmentation traits further supported species distinctions. A dark cheek bar was observed in both *S. incisa* and *S. leiurus*, while *S. strongylura* bore a distinct dark blotch on the caudal peduncle. *S. anastomella* and *S. urvillii* were both unmarked, with *S. urvillii* further distinguished by its combination of unpigmented body, truncate caudal fin, low fin ray counts, and presence of scales at the fin bases (Collette, 1984, 1999; Masuda *et al.*, 1984; Roul *et al.*, 2018). These diagnostic features, taken together, provide clear support for recognising *S. incisa*, *S. leiurus*, and *S. strongylura* as distinct and valid species within the Indian marine fish fauna.

The otolith shape and its distinguishing features are valuable tools in the taxonomy of the genus *Strongylura* from Indian waters. Although Vignon and Morat (2010) demonstrated that otolith contours undergo clear ontogenetic changes in tropical reef fishes, they emphasised that the underlying taxonomic signal remains preserved, allowing reliable species-level discrimination. The analysis of sagittal otoliths reveals key similarities and dissimilarities that can be used to differentiate species (Abdussamad, 2015). While all three species share a basic elongated, oval structure, variations in elongation and marginal characteristics serve as critical distinguishing features. For example, the moderately elongated otolith with smooth, rounded margins of *Strongylura incisa* can be used to differentiate it from the other two species. In contrast, the more compact and rounded otolith of *S. leiurus*, which has noticeably smoother and more symmetrical margins, provides a clear morphological basis for its taxonomic separation. The most unique otolith shape belongs to *S. strongylura*. Its elongated form is accompanied by prominent serrated or jagged edges, offering a distinct and reliable characteristic for species identification within the genus.

The present findings align with the established efficacy of the cytochrome c oxidase subunit I (COI) gene as a robust marker for species identification and delimitation in fishes (Hebert *et al.*, 2003; Ward *et al.*, 2005). The maximum likelihood phylogeny successfully resolved each species into a distinct clade with no overlap. A clear barcode gap was evident, characterised by minimal intraspecific K2P distances (0.0–0.6%) and comparatively high interspecific distances (17.8–23.7%). Although these interspecific values are higher than typically expected for congeneric teleosts, they likely reflect the polyphyletic nature of the genus *Strongylura*, as previously reported (Lovejoy, 2000; Lovejoy and Collette, 2001; Lovejoy *et al.*, 2004), wherein certain species exhibit closer phylogenetic affinities with genera such as *Tylosurus* and *Xenentodon*. This deep lineage divergence may contribute to the elevated genetic distances observed. Furthermore, the strong phylogenetic clustering of our Indian specimens with conspecific sequences from geographically distant regions of the Indo-Pacific (e.g., Pakistan, Indonesia, and the Philippines) not only validates species identification but also supports their broad distribution and genetic cohesion.

The present study establishes the taxonomic distinctness of *Strongylura incisa*, *S. leiurus*, and *S. strongylura* from Indian waters through an integrative approach combining detailed morphometric and meristic analyses with COI-based molecular data. Clear diagnostic differences were observed in fin ray counts, scale patterns, body proportions, and pigmentation, while phylogenetic analyses revealed well-supported clades with high interspecific and low intraspecific genetic divergence. These findings provide a robust framework for species delimitation within the genus and offer essential baseline data for future research on population structure, evolutionary relationships, and species-specific conservation strategies in Indian marine ecosystems. However, the study is based on a representative but limited sample size and geographic coverage, and further extensive sampling is recommended to validate and expand upon these findings.

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Author contributions

Conceptualisation: TT, Methodology: TT., Data Collection: TT., Writing Original Draft: TT., Supervision: TT.; Writing Review and Editing: EMA, BS; Supervision: EMA; Data Amalysis: TT, BS

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of sensitive samples/ protected environments.

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Calanoid copepod diversity and distribution with reference to abiotic factors in coastal Bay of Bengal

K. Sivakumar*, Md Anwar Nawaz, P. Muthupriya and S. V. Meenakshi
Karpaga Vinayaga College of Engineering and Technology, Chengalpattu-603 308, Tamil Nadu, India.

*Correspondence e-mail: ksivakumar76@gmail.com
ORCiD: https://orcid.org/0000-0001-8971-869X

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Original Article

Abstract

Understanding the mechanisms that maintain the diversity of plankton communities in marine waters remains a major challenge in modern oceanography. Calanoid copepods are dominant members of marine zooplankton communities. Hence, the present study focuses on the relationship between calanoid copepods and various environmental parameters on the Southeast Coast of India. Zooplankton samples were collected from January to December 2021 from three stations on the Chennai coast. Water abiotic factors, such as temperature, salinity, dissolved oxygen (DO), pH, phosphate, nitrite, nitrate, ammonia, calcium, and magnesium, were studied throughout the study period. A total of 35 calanoid species have been reported from the Coramondal coastline, which is part of the Bay of Bengal. Among these, 26 species were found in the central part of the study area (Marina), 25 species in the southern part of the study area (Kovalam), and 16 species in the northern part of the study area (Ennore). A high Shannon's diversity index was observed during February at the Marina (2.386) and Kovalam (2.543) stations. A significant negative regression coefficient was observed between the calanoid copepods and temperature, calcium, nitrite, nitrate, and ammonia. However, dissolved oxygen was observed with a significant positive regression coefficient at all stations. This study provides a detailed overview of the relationships between various calanoid species and various abiotic parameters along the tropical coast.

Keywords: *Bay of Bengal, coastal systems, environmental gradients, calanoida, copepod ecology*

Introduction

Zooplankton are primary consumers of the aquatic food chain. They are vital sources of nutrients and energy that are transferred to higher trophic levels (Al *et al.*, 2018). The dominant and ecologically important members of the marine zooplankton are copepods, especially calanoid copepods, which dominate much of the tropical and subtropical marine environment (Rajthilak *et al.*, 2016). Due to their abundance and their role in the transfer of energy, the processing of nutrients, and the stability of the food web, they are also excellent indicators of ecosystem health. This article aims to study the diversity and distribution of calanoid copepods in the aquatic ecosystems of the Chennai coast while investigating the effects of key physico-chemical factors. The present study investigates the impact of temperature, salinity, pH, and light intensity on the populations of these calanoid copepods to gain better insight into their ecological role and distribution patterns in this region (Li *et al.*, 2008; Deepika *et al.*, 2019). Copepods are useful bio-indicators, as well as playing an important trophic role; thus, understanding these interactions is important in assessing ecosystem health and predicting responses to environmental perturbations (Park and Lee, 2021)

The seasonal variability highlights the dynamic changes in both copepod communities along with environmental variables that can provide a holistic understanding of their dependability (Hussain *et al.*, 2020; De Oliveira Dias *et al.*, 2009). This provides in-depth insights into how physicochemical parameters previously identified to influence aquatic biota, drive copepod community structure and dynamics specifically in tropical estuarine systems (Riyas *et al.*, 2021; Rahman, 2021). Specifically, this study proposes that different physical-chemical gradients resemble different copepod assemblages, and that the abundance and diversity are the highest when temperature and salinity are optimal (Koçum and Sutcu, 2014; Von Weissenberg *et al.*, 2022). This work assumes nutrient availability, nitrates, phosphates, and silicates are directly linked to the abundance of copepods, primarily linked to phytoplankton growth, used as a food source (Augustine *et al.*, 2014). The predominant copepod species within ecosystems and their relative abundance along sampling sites to achieve a relatively local distribution (Zhang *et al.*, 2019). This style of study goes beyond descriptive surveys and establishes mechanistic connections between the environment and calanoid copepod community structure, greatly addressing a knowledge gap observed in tropical aquatic ecology.

The important ecological role of copepods as primary consumers and a key link to marine food webs to higher trophic levels (Wichard *et al.*, 2008; Sarker *et al.*, 2020), as well as their abundance and the overall copepod community structure, is also a direct measure of ecosystem health and productivity (Nandakumar and Perumal, 2018). It is important to understand the workings of these dynamics to forecast resilience and vulnerability of these aquatic ecosystems under climate change and anthropogenic disturbance (Mukhopadhyay *et al.*, 2007). Changes in parameters, such as temperature, salinity, and pH, can drastically affect copepod reproductive effort and developmental rates, and can also affect the colonisation of copepods by epibionts, affecting their population dynamics and community structure (Von Weissenberg *et al.*, 2022; Kumar *et al.*, 2022).

Furthermore, understanding these sensitivities is critical to assess the cumulative effects of pollution and habitat loss on coastal marine biodiversity. We consider this particularly important as the effects of port activities on plankton community dynamics in terms of abundance, composition, size structure, and nutrient cycling are well known, and calanoid copepods are sensitive to a variety of environmental factors including some that are stressors that can arise from industrial discharges (Milione and Zeng, 2008; Poloczanska *et al.*, 2013; Tibúrcio *et al.*, 2015; Shaikh *et al.*, 2021; Park and Lee, 2021). The environmental changes can result in alterations in planktonic food web-structure and ecosystem metabolism, while influencing dynamics between herbivory and nutrient cycling (Franzé *et al.*, 2022).

The studies on copepods in the southeast coast of India have primarily been descriptive in nature despite their relevance to the ecosystem. Some studies have documented species richness along the Tuticorin coast (Kavitha *et al.*, 2018), the Adayar estuary and Coovum (Shanthi and Ramanibai, 2011), and in Tamil Nadu (Krishnaswamy, 1951; Madhupratap, 1999; Gopikrishna, 2004; Dilshad Begum, 2006; Muthupriya, 2007; Santhanam *et al.*, 2012; Rajthilak *et al.*, 2016; Sivakumar *et al.*, 2021), but there has been no systematic evaluation of how other physicochemical parameters influence copepod diversity and distribution in these systems. Similarly, the study aims to find out whether changes in circulation of the ocean, which are largely influenced by thermal gradients, can affect copepod distributions and the higher biota, including commercially exploited species (Qiu, 2001). Therefore, this study will present a very useful baseline for monitoring the health of coastal ecosystems as environmental change continues, and also for future ecotoxicological studies using copepods as bio-indicators (Nguyễn *et al.*, 2020; Park and Lee, 2021). This research will therefore shed light on copepod stress response (resilience and adaptation) to multi-stressors, which is becoming increasingly relevant at a global scale, while the results will also assist predictions of future climate scenarios on marine productivity and fisheries, with specific emphasis on copepods' role in the stability of ecosystems.

Material and methods

Study area

Zooplankton samples were collected from three coastal stations in the Bay of Bengal, representing varying levels of anthropogenic impact: (Fig. 1) (Mantha *et al.*, 2012): Ennore (13°12′ 23.49″ N, 80° 19′ 38.01z E) – Impacted by industrial effluents, fly ash, thermal discharges, dredging, and fishing activities, Marina (13° 03′ 00″ N, 80° 16′ 56.64″ E) – Affected by domestic sewage and tourism, Kovalam (12° 47′ 13.2″ N, 80° 15′ 1.44″ E) – Comparatively pristine, with minimal industrial influence.

Sampling design and zooplankton collection

Sampling was conducted monthly from January to December 2021 during early morning hours. At each station, horizontal and 20 m vertical tows in triplicate were conducted 5 nautical miles offshore using a plankton net with a 150 µm mesh. The net (mouth diameter: 0.5 m) was towed at a constant speed of approximately 2 knots for 15 minutes using a dinghy boat. In the absence of a flowmeter, theoretical volume ($V = \varpi r^2 L$) was calculated, where length (L) was derived from GPS-recorded towing speed and time. The samples were filtered through a 150 µm sieve and preserved in 5% buffered formalin. Minimal disturbance during retrieval ensured sample integrity.

Taxonomic identification and enumeration

In the laboratory, zooplankton samples were examined under a stereomicroscope (Labovision KS f2000). Only adult calanoid copepods were dissected and identified using standard taxonomic keys (Kasturirangan, 1963; Boxshall and Halsey, 2004; Razouls *et al.*, 2022). Dissected appendages were mounted on slides and examined using a trinocular microscope (Olympus CH21(I)) with camera lucida support. To enhance ecological resolution, copepodite stages were

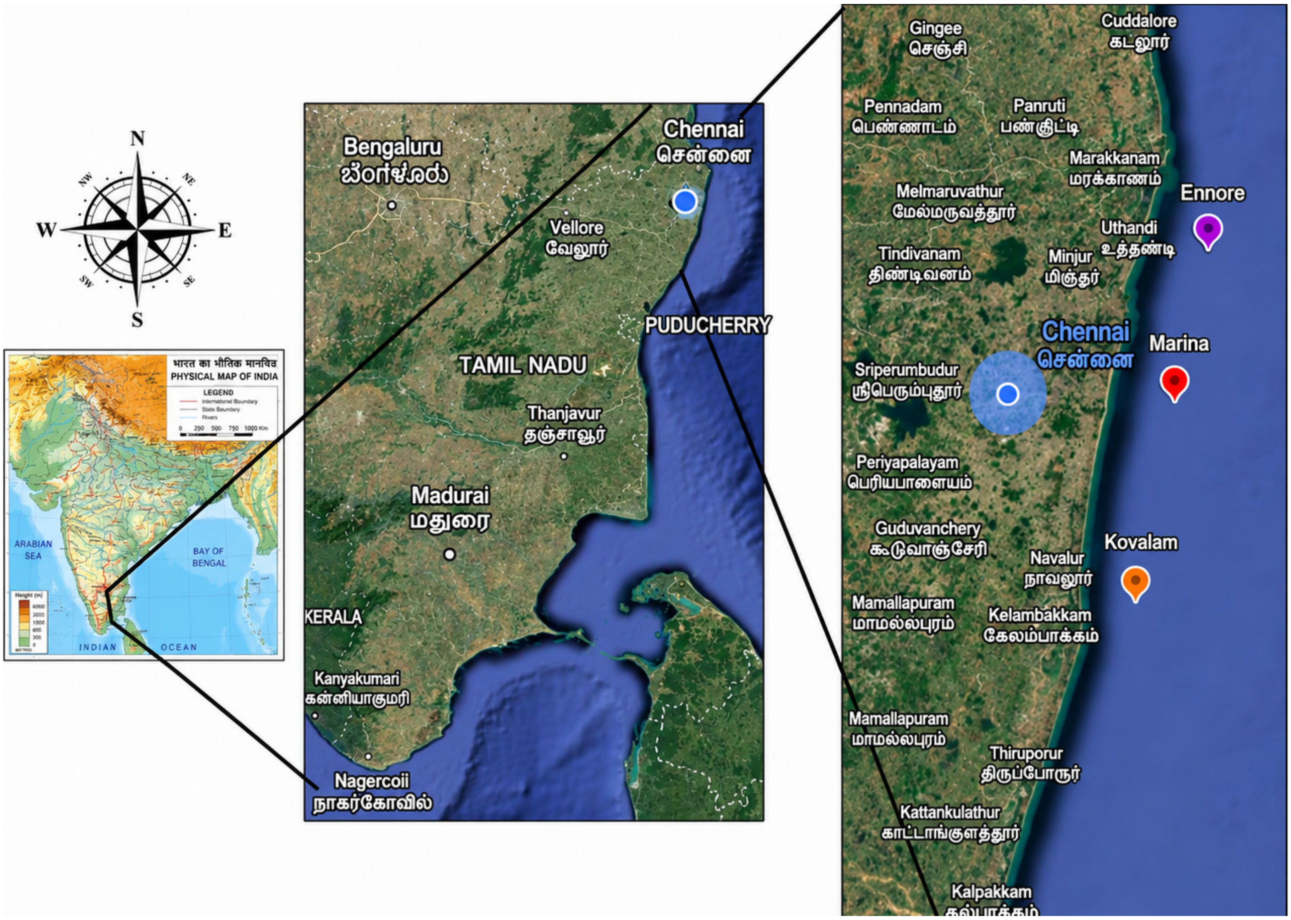


Fig. 1. Sampling stations

also counted. This allowed better assessment of recruitment and temporal dynamics.

Density estimation

Quantification was conducted using a Sedgwick-Rafter counting chamber, with triplicate subsamples per tow. The average count was used for calculating densities per cubic meter (Perry, 2003):

Number of calanoid copepods per cubic meter
= Average numbers in the drops xTotal drops in entire sample/Volume

where Volume = $\pi r^2 L$ and Length (L) is derived from the equation = Speed × Time.

The average number of animals per drop was calculated as follows:

Average numbers in the drops
= Numbers of animals observed/Number of drops analysed

Physico-chemical measurements

Water samples were collected simultaneously using a Niskin water sampler (2.5 L). Water samples were collected at the same depth as the zooplankton samples, and the physico-chemical parameters were analysed to ensure homogeneity between the environmental and biological data. In situ parameters included temperature (mercury thermometer), salinity (ERMA RHS 10 ATC), pH (LUTRON PH-210), and DO (LUTRON DO 5510). Calcium and magnesium levels in seawater were determined using a standard method and titrated to the photometric endpoint using EDTA (Malmstadt and Hadjiioannou, 1959). Phosphate, nitrite, nitrate, and ammonia levels were measured according to the standard manual (Strickland and Parsons, 1972). The concentration of nitrite (NO_2) was determined by the formation of a bright azo dye, colourimetrically measured at 540 nm (Wood *et al*., 1967). Nitrate (NO_3) was measured using the ammonium chloride method following a standard procedure (Strickland and Parsons, 1972). Inorganic phosphate (PO_4) in seawater was analysed using a colourimetric method that produces a brightly colored phosphomolybdate compound (Murphy and Riley, 1962). Ammonia was determined by treating seawater with sodium hypochlorite and phenol in the presence of sodium nitroprusside in alkaline citrate medium (Solórzano, 1969).

Statistical analysis

Data were expressed as mean ± SD, and statistical analyses were performed using SPSS v26.0 and PAST v4.09. One-way ANOVA followed by Tukey's post hoc test ($p < 0.05$) was used to assess significant differences among stations and species. Repeated measures of ANOVA were performed between Stations vs Month and Stations vs Seasons. Pearson correlation analysis was conducted to examine relationships among environmental parameters. Before constrained ordination, Detrended Correspondence Analysis (DCA) was performed. The original axis gradient length was less than 3 standard deviation units, indicating a linear species–environment relationship. According to the recommended criteria, when the gradient length is less than 3, linear methods such as Redundancy Analysis (RDA) are appropriate. Redundancy analysis (RDA) and cluster analysis were carried out using Bray-Curtis similarity indices to evaluate species-environment relationships. Assumptions of normality and homogeneity of variance were tested using the Shapiro-Wilk and Levene's tests, respectively.

Results and discussion

Physicochemical parameters

Fig. 2 and 3 show a comparison between the different stations' water physicochemical parameters. The water temperature varied between 25.3 and 33.9 °C from all stations throughout the study period. High mean temperature was observed during May (33.9 ± 0.9 °C), and low temperature was observed during January (26.2 ± 0.5 °C) (Fig. 2a). Low salinity, dissolved oxygen, and pH were observed from May to July at all stations (Fig. 2 b-d). Ennore station was observed with low dissolved oxygen levels (4.5 ± 0.68 mgL^{-1}) compared to Marina (5.11 ± 0.55 mgL^{-1}) and Kovalam (5.17 ± 0.86 mgl^{-1}), Nitrite and phosphate content were high at Ennore station (2.9 ± 0.71 mgl^{-1} and 1.3 ± 0.57 mgl^{-1} respectively) compared to Marina (2.4 ± 0.62 mgl^{-1} and 1.1 ± 0.45 mgl^{-1}) and Kovalam (2.3 ± 0.52 mgl^{-1} and 1.1 ± 0.51 mgl^{-1}) (Fig. 3a and 3b). Ammonia levels were also higher at the Ennore station (0.04 ± 0.006 mgl^{-1}) compared to Marina (0.035± 0.003 mgl^{-1}) and Kovalam (0.033 ± 0.008 mgl^{-1}) (Fig. 3d). Monthly high nutrient content in water was reported from October to December from all stations. Calcium and magnesium levels varied between (350 - 430 mgL^{-1} and

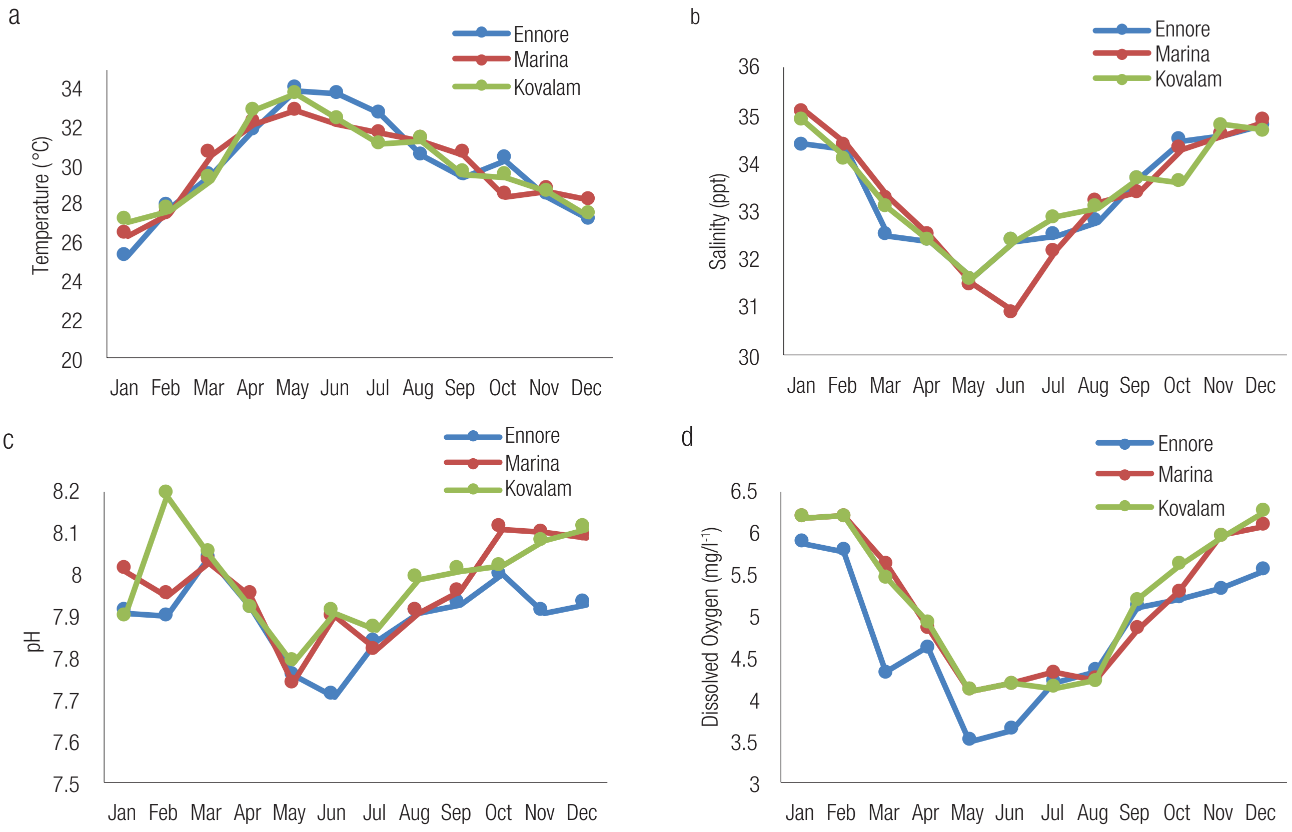


Fig. 2. a) Temperature, b) Salinity, c) pH and d) Dissolved Oxygen in Ennore, Marina and Kovalam stations

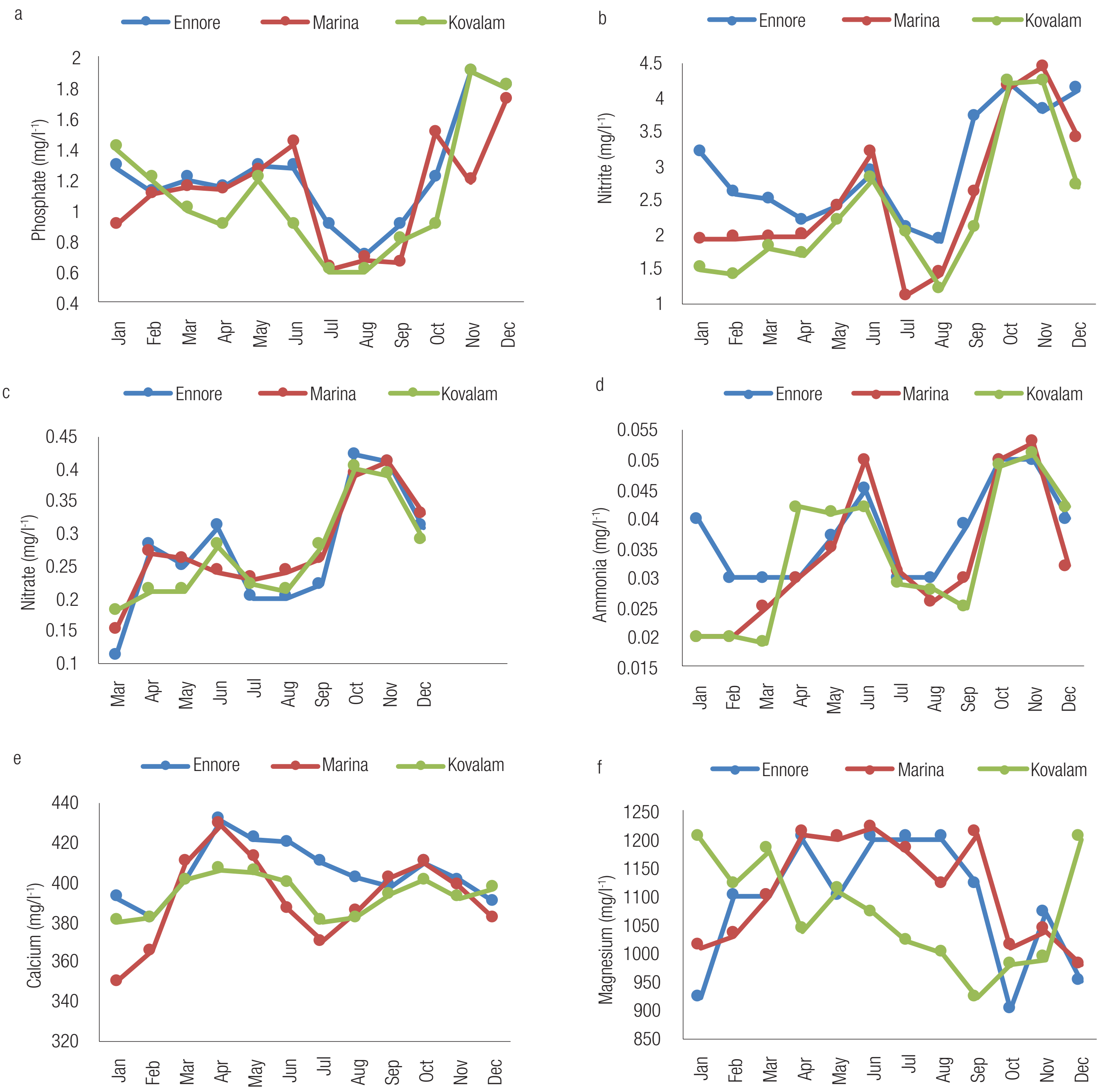
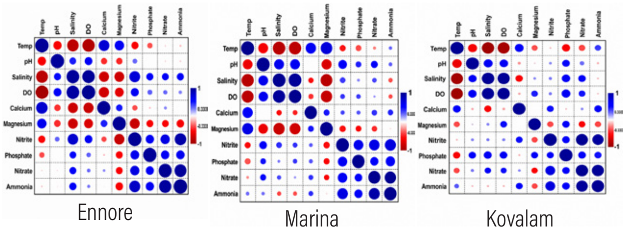


Fig. 3.a) Phosphate, b) Nitrite, c) Nitrate, d) Ammonia, e) Calcium and f) Magnesium levels in Ennore, Marina and Kovalam stations

900 - 1210 mgl^{-1}, respectively) (Fig 3e and f) throughout the study period. Fig. 4 shows correlation coefficients between various physicochemical parameters from all three stations. A high negative correlation coefficient was observed between temperature and dissolved oxygen, salinity, and pH at all stations. Dissolved oxygen content is known to be affected by water temperature, as oxygen is more soluble in colder water than in warmer water (Harvey *et al*., 2011).



Ennore Marina Kovalam

Fig. 4. Correlation coefficients between physicochemical parameters

Spatial and temporal variations in calanoid copepods

In the present study, 35 species of calanoid copepods were reported from all 3 stations, with the highest number of 26 species observed in Marina, followed by 25 species in Kovalam, and 18 in Ennore (Table 1). *Acrocalanus gracilis* was observed to be the dominant species with an abundance of 626.6 ± 98.4 x10^{3} ind.m^{-3}, 766.6 ± 21.2 x10^{3} ind.m^{-3}, 698.6 ± 13.5 x10^{3} ind.m^{-3} from Ennore, Marina, and Kovalam, respectively. *Mesocalanus tenucornis* (5 ± 3.4 x10^{3} ind.m^{-3}) in Ennore, *Labidocera minuta* (5.3 ± 3 x10^{3} ind.m^{-3}) in Marina and *Pontella danae* (2 ± 1 x10^{3} ind.m^{-3}) in Kovalam showed low density throughout the study period. Kavitha *et al.* (2018) also reported *A. gracilis* as a dominant calanoid species from the coast of Tuticorin, south India. Paracalanidae copepods are generally predominant in tropical and subtropical regions (Cornils and Blanco-Bercial, 2013). High mean density was observed during February from all three stations: Ennore (239.6 ± 9.01 x10^{3} m^{-3}), Marina (281 ± 14.7 x10^{3} ind.m^{-3}) and Kovalam (294.3 ± 14.2 x10^{3} ind.m^{-3}) (Table 2). However, low density was observed during July in Ennore (113.3 ± 16.6 x10^{3} ind.m^{-3}), October in Marina (175.6 ± 17.8 x10^{3} ind.m^{-3}) and June in Kovalam (185 ± 2.6 x10^{3} ind.m^{-3}). Overall, high density is observed in Marina (219.02 ± 17.4 x10^{3} ind.m^{-3}) and low density is observed in Ennore (170.3 ± 10.3 x10^{3} ind.m^{-3}). The current study showed substantial variation in calanoid copepod density between Marina and Ennore stations ($p < 0.05$), but not between Marina and Kovalam stations, as revealed by Tukey's post hoc test. The notable difference in the density of calanoids at Ennore and Marina can be explained based on physicochemical factors, such as availability of nutrients, load of pollutants, and hydrodynamic regime, which have been found to contribute significantly to the spatial distribution of plankton communities (Govindasamy *et al.*, 2000; Santhanam and Perumal, 2003).

Table 1. Mean density (x10^{3} ind.m^{-3}) of calanoid copepods of Ennore Marina and Kovalam stations

Family	Species	Ennore	Marina	Kovalam
Acartiidae	*Acartia tonsa* (Dana,1849)	-	36.6 ± 4^{abc}	-
	Acartia erythrea (Giesbrecht, 1889)	118 ± 15.7^{a}	83 ± 12.1^{abcd}	97.3 ± 8.9^{a}
	Acartia spincauda (Giesbrecht, 1889)	118 ± 15.7^{a}	35.6 ± 7.2^{abc}	86.3 ± 9.4^{a}
Paracalanidae	*Acrocalanus gibber* (Giesbrecht, 1888)	289.6 ± 5.8^{b}	276.3 ± 9.07^{abc}	175 ± 6.5^{a}
	Acrocalanus gracilis (Giesbrecht, 1888)	626.6 ± 98.4^{c}	766.6 ± 21.2^{e}	698.6 ± 13.5^{b}
	Paracalanus parvus (Claus, 1863)	83 ± 8.7^{a}	32.3 ± 5.6^{abc}	-
	Paracalanus aculeatus (Giesbrecht, 1888)	19.6 ± 6.5^{a}	-	-
Calanidae	*Canthocalanus pauper* (Giesbrecht, 1888)	133.6 ± 25.6^{a}	233.3 ± 4.9^{d}	259.6 ± 24.1^{a}
	Mesocalanus tenuicornis (Dana,1849)	5 ± 3.4^{a}	-	-
Centropagidae	*Centropages furcatus* (Dana,1849)	-	36.3 ± 3.5^{abc}	67 ± 8.8^{a}
	Centropages tenurinis (Thompson I.C and Scott A, 1903)	61.6 ± 8.08^{a}	136.3 ± 11.6^{abcd}	54.6 ± 7.3^{a}
	Centropages dorsispinatus (Thompson and Scott, 1903)	-	13.6 ± 6.02^{a}	-
	Centropages orsini (Giesbrecht, 1889)	-	-	62.6 ± 7.5^{a}
Eucalanidae	*Subeucalanus monachus* (Giesbrecht, 1888)	20.3 ± 0.5^{a}	58.3 ± 2.8^{abcd}	30.3 ± 5.03^{a}
	Subeucalanus subcrassus (Giesbrecht. 1888)	107.3 ± 10.06^{a}	99.6 ± 12.5^{abcd}	128.6 ± 7.5^{a}
Candaciidae	*Candacia discaudata* (Scott A, 1909)	-	27 ± 1^{abc}	34.3 ± 2.5^{a}
Euchaetidae	*Euchaeta marina* (Prestandrea, 1833)	-	17.6 ± 3.5^{ab}	-
Lucicutiidae	*Lucicutida flavicornis* (Claus, 1863)	-	20 ± 2^{ab}	-
Pontellidae	*Labidocera pavo* (Giesbrecht, 1889)	-	-	39 ± 4^{a}
	Labidocera acuta (Dana, 1849)	6.6 ± 3.05^{a}	28 ± 2.6^{abc}	46 ± 6.9^{a}
	Labidocera minuta (Giesbrecht, 1889)	35.6 ± 3.2^{a}	5.3 ± 3^{a}	4.6 ± 2.5^{a}
	Labidocera bengalensis (Krishnaswamy, 1952)	-	46 ± 2.1^{abc}	103 ± 15.8^{a}
	Calanopia minor (Scott A., 1902)	-	-	26.3 ± 2.3^{a}
	Calanopia aurivilli (Cleve, 1901)	-	-	27 ± 5^{a}
	Calanopia elliptica (Dana, 1849)	-	22.6 ± 5.03^{ab}	40.6 ± 7.3^{a}
	Pontella danae (Giesbrecht, 1889)	-	-	2 ± 1^{a}
	Pontellopsis scotti (Sewell, 1932)	-	-	2.6 ± 2^{a}
	Pontellopsis herdmani (Thompson I.C. and Scott A., 1903)	-	-	6.6 ± 3.5^{a}
Pseudodiaptomidae	*Pseudodiaptomus serricaudatus* (Scott T, 1984)	99 ± 4^{a}	209.7 ± 4.1^{bcd}	225.6 ± 12.8^{a}
	Pseudodiaptomus annandelei (Sewell, 1919)	15.3 ± 3.05^{a}	46 ± 3^{abc}	-
	Pseudodiaptomus aurivillii (Cleve, 1901)	71 ± 8.7^{a}	41 ± 4.3^{abc}	-
Temoridae	*Temora turbinata* (Dana, 1849)	274.6 ± 25.7^{b}	215.6 ± 10.6 ^{cd}	246.6 ± 16.2^{a}
	Temora discaudata (Giesbrecht. 1889)	-	79.6 ± 1.5^{abcd}	95.3 ± 11.1^{a}
	Temora stylifera (Dana, 1849)	47 ± 4.5^{a}	40.3 ± 3.2^{abc}	54.6 ± 6.3^{a}
Tortanidae	*Tortanus forcipatus* (Giesbrecht. 1889)	-	21 ± 8.5^{ab}	-
	Copepodid	3097.77 ± 342.67^{d}	3520.65 ± 444.62^{f}	3594.09 ± 737.12^{c}
	Nauplius	3554.40 ± 348.24^{e}	3834.42 ± 375.19^{g}	3931.92 ± 566.45^{d}
F value		270.916	230.105	93.598
P value		0.000	0.000	0.000

Species with the same alphabet superscripts in a column denote they were grouped in ANOVA followed by DMRT's test ($p<0.05$).

- denotes absence of the species

Table 2. Density (x10^3 ind.m^{-3}) of calanoid copepods at different months

Months	Ennore (x10^3 ind.m^{-3}) (mean±SD)	Marina (x10^3 ind.m^{-3}) (mean±SD)	Kovalam (x10^3 ind.m^{-3}) (mean±SD)
Jan-2021	171.6 ± 27.3	231 ± 10.5	248.6 ± 12.09
Feb-2021	239.6 ± 9.01	281 ± 14.7	294.3 ± 14.2
Mar-2021	162.6 ±7	219.6 ± 12.3	233.3 ± 7.5
Apr-2021	164 ± 17.8	201.3 ± 20.7	214.6 ± 12.6
May-2021	179.6 ± 21.1	186.3 ± 20.5	191 ± 9.8
Jun-2021	169.3 ± 42.1	204.6 ± 23.4	185 ± 2.6
Jul-2021	113.3 ± 16.6	239 ± 17.6	201.3 ± 6.3
Aug-2021	203.3 ± 15.6	265 ± 19.4	224.3 ± 23.6
Sep-2021	157.3± 19.1	229.3 ± 9.7	229 ± 7.2
Oct-2021	157 ± 20.7	175.6 ± 17.8	204.6 ± 5.5
Nov-2021	165.3 ±14.7	183.3 ± 22.05	199.6 ± 15.04
Dec-2021	159.3 ± 7.5	212 ± 20.07	189 ± 8
Mean	170.2 ± 20.6^a	219.02 ± 17.4^b	217.9 ± 10.3^b

Stations with the same alphabet superscripts in the column denote they were grouped in ANOVA followed by Tukey's test ($p<0.05$).

Ennore, an industrially influenced estuarine area, tends to have greater organic pollution and consequent nutrient enrichment, which favours increased plankton productivity. Marina, a coastal station with high tidal flushing and reduced pollution input, could provide suboptimal conditions for calanoid copepod congregation. The lack of large variation between the Marina and Kovalam stations is consistent with previous research by Sivakumar *et al.* (2021), where coastal water masses with comparable hydrodynamic regimes were found to have a homogeneous plankton distribution.

Additionally, the irregular distribution of calanoid copepods, which is typical of planktonic organisms, supports the non-normal distribution patterns observed in the current study. This finding concurs with Madhupratap's (1999) report that the aggregation of calanoid copepods in marine communities depends on both biological interactions and hydrographical conditions. Seasonal variations observed in the data are probably caused by variations in temperature and salinity, rainfall, nutrient loading, and phytoplankton blooms, as observed in a study in a tropical estuarine system (De Oliveira Dias *et al.*, 2009). The most common copepod species also vary seasonally, as variable species are appropriate for variable situations (De Oliveira Dias *et al.*, 2009). Geographical variations in copepod abundance are caused by upwelling (Giraldo *et al.*, 2009). The present results highlight the necessity for long-term monitoring and spatial mapping of plankton communities to further elucidate the drivers of their distribution in dynamic coastal systems.

Repeated measures of ANOVA indicated main effects of Station (F (2,4) = 23.46, $p = 0.006$), Month (F (11,22) = 227.73, $p < 0.001$), and a significant effect for Station × Month (F (22,44) = 2.35, $p = 0.008$), indicating that temporal variation was significantly different between sampling stations. Two-way repeated measures ANOVA indicated significant main effects of Station (F (2,4) = 21.43, $p = 0.007$), Season (F (3,6) = 224.50, $p < 0.001$), and a significant Station × Season interaction (F (6,12) = 3.98, $p = 0.020$), which confirmed that sample locations dynamically responded to particular seasons across the region (Table 3).

The dominance and diversity indices of the calanoid copepods are listed in Table 4. Increased dominance at Ennore shows decreased species evenness and several dominant species, whereas Kovalam supports an even species distribution. The increased Shannon diversity at Kovalam shows that it has a more stable and diverse community than Ennore, where ecological stress was higher. The Simpson dominance index (D) and Shannon diversity index (H) showed significant spatial differences in the plankton community structure between the Ennore, Marina, and Kovalam stations. The dominance index was maximum at Ennore, indicating that some species dominate the ecosystem, which agrees with earlier findings emphasising industrial pollution and eutrophication-induced

Table 3. Repeated Measures Anova of calanoid copepods between Stations vs Months and Stations vs Seasons

Parameters	Station/ Months	F-value	df	p-value	Interpretation
Stations vs Months	Station	23.46	(2, 4)	0.0062*	Significant
	Month	227.73	(11, 22)	< 0.001*	Highly significant
	Station × Month	2.35	(22, 44)	0.0079*	Significant
Stations vs Seasons	Station	21.43	(2, 4)	0.0073*	Significant
	Season	224.50	(3, 6)	< 0.001*	Highly significant
	Station × Season	3.98	(6, 12)	0.0201*	Significant

Table 4. Dominance and Diversity indices of calanoid copepods at different stations

Months	Simpson dominance (D) index			Shannon diversity (H) index		
	Ennore	Marina	Kovalam	Ennore	Marina	Kovalam
January	0.1626	0.1566	0.1058	1.723	2.121	2.421
February	0.154	0.1181	0.0931	2.104	2.386	2.543
March	0.1579	0.1432	0.1265	1.93	2.127	2.247
April	0.2248	0.1730	0.1356	1.668	1.98	2.164
May	0.2058	0.1696	0.1565	1.684	2.002	2.05
June	0.1879	0.1643	0.1523	1.805	2.01	2.056
July	0.1520	0.1160	0.1420	1.909	2.393	2.185
August	0. 1382	0.1095	0.1340	2.122	2.44	2.25
September	0. 2189	0.1491	0.1313	1.746	2.099	2.205
October	0. 1769	0.1978	0.1414	1.849	1.813	2.195
November	0.1941	0.1847	0.1532	1.781	1.88	2.091
December	0.2253	0.1524	0.1524	1.634	2.136	2.136

species changes in estuaries (Govindasamy *et al.*, 2000). The availability of pollutants and organic enrichment frequently encourages the proliferation of pollution-resistant species, and species evenness decreases. Conversely, Kovalam had the lowest dominance index and highest Shannon diversity index, indicating a more stable and diverse plankton community, in agreement with earlier observations in less disturbed coastal waters (Santhanam and Perumal, 2003). The increased diversity at Kovalam may be attributed to improved water quality, increased mixing, and lower anthropogenic disturbances, promoting a more heterogeneous and balanced plankton community.

As reported in previous studies on dynamic hydrographic coastal ecosystems, Marina stations reflect moderate dominance and diversity due to tidal influences and fluctuating environmental conditions (Madhupratap, 1999). The absence of any appreciable differences in diversity between Marina and Kovalam (as revealed by Tukey's test) implies comparable environmental conditions and connectivity among these coastal regions. In general, the results affirm the role of anthropogenic activities and natural hydrodynamic processes in controlling plankton community structure, with a focus on continued monitoring and conservation efforts in ecologically sensitive areas, such as Ennore.

Various fishing activities and waste discharge from the Ennore thermal power plant probably make Ennore the site with the lowest biodiversity compared to other stations. The bioaccumulation of trace metals in various fish species has also been observed in the Ennore Creek (Jayaprakash *et al.*, 2015). Ennore Creek also reported a very low diversity of foraminifera and benthic harpacticoid copepods (Nagendra *et al.*, 2015; Mantha *et al.*, 2012). According to a study conducted by Sivaswamy (1990) on the water bodies of Ennore, the pollution levels of Ennore water and sediments are above the safe limit. However, Sivakumar *et al.* (2021) reported high species diversity of calanoid copepods at the Marina station. Sugumaran *et al.* (2009) conducted a study on the meiofauna of Chennai coast, which showed high diversity of meiofauna in Marina station as compared to Royapuram and Pulicat. Similarly, Mantha *et al.* (2012) reported a high density of harpacticoid copepods and meiobenthic fauna on the Chennai coast during February.

Distribution patterns in calanoid copepods

The Bray-Curtis cluster diagram expressed the relationship between calanoid copepods. Dendrograms visually depict the relationships and similarities between different species (Fig. 5). The vertical axis is similarity, with higher values showing greater resemblance. The dendrogram shows clear groupings, suggesting potential ecological or genetic connections between the species. *M. tenuicornis* and *Labidocera acuta* are the outliers, with a greater difference from other clusters in the Ennore stations. Some species, such as *Acrocalanus gracilis* and *Labidocera minuta*, are more diverged from most, and these have their clusters with a higher dissimilarity index in the Marina Station. In the Kovalam station, *Pontella danae, L. minuta*, and *Pontellopsis herdmani* were distinct and had their cluster, showing lesser similarity with other species. These species may occupy different ecological niches. The species found at the Kovalam

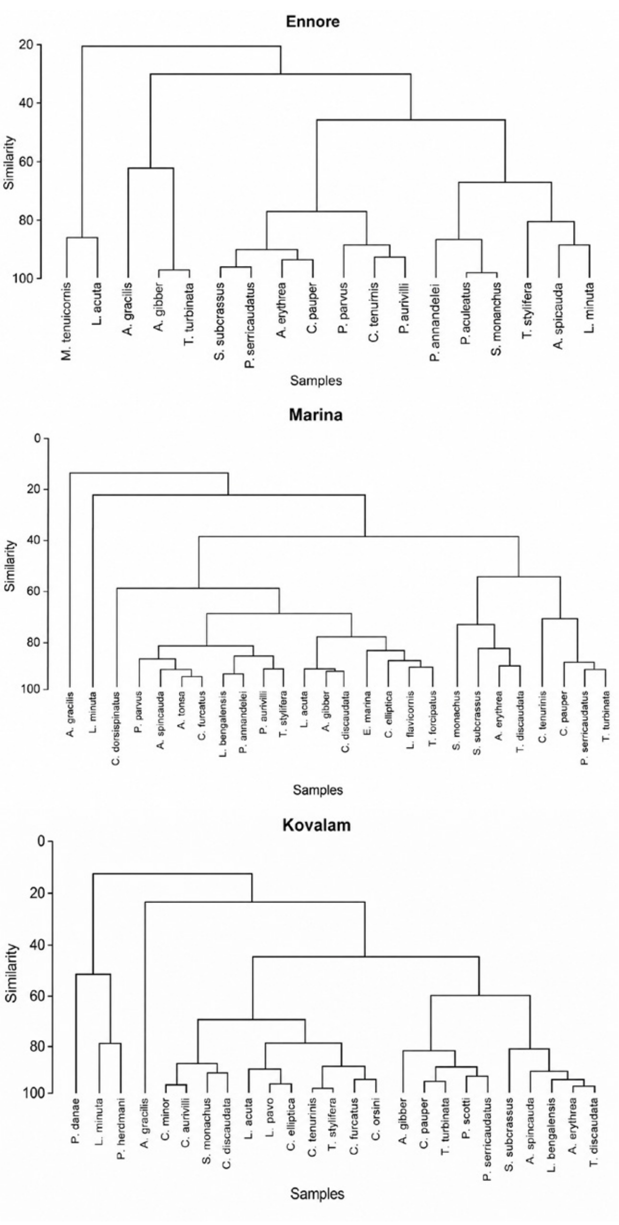


Fig. 5. Cluster dendrogram of calanoid copepods assemblage at different stations

station are differently ordered compared to those found in Marina and Ennore stations, indicating potential differences in the environment. The *A. gracilis* was present at all three locations, but with variation. The penetration of oceanic water masses into the nearshore areas due to seasonally caused hydrographic variations could have made them shift. Such spatial heterogeneity in the structure of zooplankton communities has been noted in other nearshore systems on the Indian coast (De Los Ríos *et al*., 2019), with salinity gradients, nutrient availability, and anthropogenic factors likely driving such patterns (Ratnam *et al*., 2022). The episodic presence of mesopelagic copepods in coastal waters has been reported in the Bay of Bengal and the Arabian Sea through monsoonal changes and eddies (Madhupratap *et al*., 1999). *Euchaeta marina* and *L. flavicornis* in near-surface collections could also signal passive entrainment or transitory recruitment from deeper water following the disruption of cues for vertical migration by shifts in light penetration or salinity gradient (Yamaguchi *et al*., 2002).

Interaction between calanoids and physico-chemical parameters

Regression analysis of calanoid copepod abundance with physico-chemical parameters at the Ennore stations indicated that none of the parameters were statistically significant predictors at 5% significance level, nevertheless dissolved oxygen ($\beta = 0.899$, p = 0.156) and calcium ($\beta = 0.606$, p = 0.098) showed relatively strong positive associations, which suggests that these parameters may support calanoid copepod populations by supporting the metabolism associated with aerobic respiration and exoskeleton formation, respectively. However, there were also statistically significant negative effects of temperature ($\beta = -0.848$, p = 0.082) and nitrite ($\beta = -0.442$, p = 0.152) (Table 5).

Table 5. Regression coefficient of calanoid copepods with physicochemical parameters at different stations

Parameters	Ennore	Marina	Kovalam
Temperature (^{0}C)	-0.848 (0.082)*	-1.174 (0.301)	-0.648 (0.122)
pH	-0.303 (0.129)	-0.607 (0.360)	-0.288 (0.118)
Salinity (ppt)	0.102 (0.731)	0.232 (0.716)	0.286 (0.348)
Dissolved Oxygen (mg/l^{-1})	0.899 (0.156)	-0.001 (0.999)	0.529 (0.199)
Calcium (mg/l^{-1})	0.606 (0.098)	0.653 (0.356)	0.500 (0.081)
Magnesium (mg/l^{-1})	0.109 (0.404)	0.426 (0.293)	-0.316 (0.120)
Nitrite (mg/l^{-1})	0.442 (0.152)	0.630 (0.300)	-0.506 (0.148)
Phosphate (mg/l^{-1})	-0.169 (0.217)	0.072 (0.700)	0.171 (0.197)
Nitrate (mg/l^{-1})	-0.491 (0.147)	0.374 (0.296)	0.184 (0.459)
Ammonia (mg/l^{-1})	0.128 (0.497)	-0.759 (0.188)	-0.104 (0.495)

*within parentheses mentioned p-value

The regression analysis between calanoid copepod abundance and physico-chemical parameters at the Marina stations showed that none of the variables demonstrated to be statistically significant at the 5 % level. However, calcium ($\beta = 0.653$, p = 0.258), magnesium ($\beta = 0.426$, p = 0.293), nitrite ($\beta = 0.630$, p = 0.306), and nitrate ($\beta = 0.374$, p = 0.296) indicated relatively strong, positive associations with the abundance of calanoid copepods and possibly contribute to the growth of calanoid copepods via structural contributions or nutritional aspects. Temperature ($\beta = -0.174$, p = 0.301), pH ($\beta = -0.567$, p = 0.360), dissolved oxygen ($\beta = -0.001$, p = 0.999), phosphate ($\beta = 0.072$, p = 0.700), and ammonia ($\beta = -0.759$, p = 0.188) (Table 5) indicated weak or negative associations, therefore may contribute to possible stress aspects or limited control over calanoid copepod abundance.

The regression analysis of calanoid copepod abundance and physico-chemical parameters at the Kovalam stations showed that none of the parameters had a significant enough effect at the 5% level; however, dissolved oxygen and calcium exhibited relatively stronger positive relationships ($\beta = 0.529$, p = 0.199; $\beta = 0.500$, p = 0.081) (Table 5), signifying their potential ecological relevance to calanoid copepods. The results indicate that, despite the relatively weak statistics, environmental factors may have a significant influence on calanoid copepod distribution.

The redundancy analysis (RDA) ordination indicates that the first two canonical axes explain most of the joint variation between the measured physico-chemical variables and calanoid copepod density at the three stations (Ennore, Marina, Kovalam). Axis 1 is chiefly related to temperature, salinity, pH, dissolved oxygen, nitrate and ammonia, which positively load and cluster with high-density calanoid copepod samples across all study months, indicating that warmer and more saline, and oxygenated waters with higher nitrogen forms favoured greater calanoid copepod abundance. Axis 2 is understood to be associated with phosphate, magnesium, and calcium, which point away from the majority of the calanoid copepod points, indicating that the relationship of these nutrients with calanoid copepod density was comparatively weaker or possibly even negative. Seasonal clustering is evidence that shows winter months clustered toward the negative side of Axis 1, where

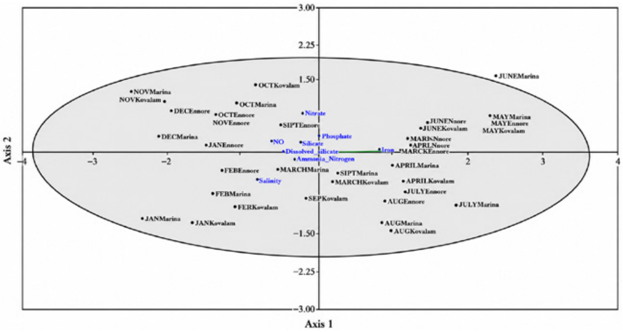


Fig. 6. Redundancy Analysis (RDA) of calanoid copepods and physico-chemical parameters at different stations

the nutrient concentrations were lower, while summer months were clustered toward the positive side, where these physico-chemical characteristics peaked, where temperature and nitrogen compounds were at their highest, and corresponded to increases in calanoid copepod counts. Overall, the RDA suggests that temperature, salinity, pH, dissolved oxygen, and nitrogenous nutrients may be the key drivers of spatial-temporal variations in calanoid copepod density at the three coastal stations, while phosphorus, magnesium, and calcium may exert minor influences (Fig. 6). RDA shows environmental gradients linked to calanoid copepod distribution. The statistical relationship is weak when the variables are tested separately, as seen in regression analysis.

Acartia species are capable of producing three types of eggs: subitaneous eggs (they hatch immediately in most cases unless environmental conditions are unfavourable), diapause eggs (development is stopped for a while), and delayed hatching eggs (they hatch after a longer period of time when conditions are suitable) (Tsunashima *et al.*, 2021). It is known that temperature is an important abiotic component affecting the biological activities of organisms at all levels, and marine invertebrates such as crabs and fish often shift their geographic distribution in response to temperature fluctuations (Milione and Zeng, 2008). It also affects the seasonal and geographic distributions of marine calanoid copepods (Abo-Taleb *et al.*, 2020). However, dissolved oxygen is vital to aquatic organisms, and low dissolved oxygen levels indicate water pollution, which leads to the death of an organism (Bozorg-Haddad *et al.*, 2021). Likewise, high levels of ammonia are toxic to aquatic organisms and reduce the hatching rate of calanoid copepod eggs (Eddy, 2005). Nitrite is a naturally occurring component of the nitrogen cycle in ecosystems and has been shown to cause several physiological disorders in aquatic organisms, even at low concentrations (Carmargo, 2005). Although nitrates are less toxic than nitrites, they are known to convert oxygen-transporting pigments into ineffective forms, resulting in lower oxygen uptake by aquatic organisms. However, the toxicity of nitrates to aquatic invertebrates increases with increasing nitrate concentration in the water and with increasing exposure time, and decreases with increasing body size (Jensen, 2003). High concentrations of nitrite, nitrate, phosphate, and ammonia also cause the rapid growth of phytoplankton in aquatic ecosystems, which in turn reduces copepod productivity (Umer *et al.*, 2020). High phytoplankton density causes an algal bloom, which leads to the production of various toxins that are dangerous to calanoid copepods. Calcium and magnesium are essential for many biological processes; however, at high quantities, they can be hazardous to aquatic organisms (Van Dam *et al.*, 2010). The present study has revealed that the station Ennore showed a lower value of dissolved oxygen with higher concentrations of ammonia, nitrite, calcium and phosphate compared to other stations. This difference explains the lower abundance and geographic range of calanoid copepods at this site. During February, all the stations had high levels of dissolved oxygen and low temperatures, coinciding with the highest values of calanoid copepods. Salinity also plays an important role in copepod distribution, as very high and low salinity levels reduce copepod hatching success (Peck *et al.*, 2015). Lee *et al.* (2020) observed a low egg production rate in copepods in a low pH environment. The salinity pH of Ennore and Kovalam are found to be the least in June and July in the present study. This provides a probable reason why fewer calanoid are in evidence at this time. But the water has a high nutrient content in October, so the Marina's density is low.

Conclusion

In the present study, the relationship between calanoid copepods density and physico-chemical parameters was studied in the sub-plankton region over three stations of the Chennai coast. While temperature, dissolved oxygen, calcium and selected nutrients had significant relationships with calanoid abundance in regression analyses, most of these could not be considered as drivers $p > 0.05$ but rather indicative trends. Lower calanoid density at Ennore was simultaneous with higher ammonia and nitrite, and lower dissolved oxygen, while higher densities in February were associated with high dissolved oxygen and low temperature. These observations indicate that the seasonal hydrographic state, predominantly linked to DO variability, could modulate calanoid occupancy. Long-term investigations are suggested to provide a more complete characterisation of these interactions.

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Author contributions

Conceptualisation: KSK; Methodology: KSK; Data Collection: MAN, PMP, SVM; Data Analysis: MAN, PMP, SVM; Writing Original Draft: MAN, PMP, SVM; Writing Review and Editing: KSK, Supervision: KSK.

Data availability

The data are available and can be requested from the corresponding author

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of sensitive samples/ protected environments.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

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Species diversity and distribution of croakers (Acanthuriformes: Sciaenidae) from Indian waters: Insights from a comprehensive survey

A. T. Sangeetha[1,2]*, Rekha J. Nair[1] and K. M. Vishnupriya[1,2]
[1]ICAR- Central Marine Fisheries Research Institute, Kochi-682 018, Kerala, India.
[2]Cochin University of Science and Technology, Kochi-682 022, Kerala, India.

*Correspondence e-mail: rekha.j@icar.org.in
ORCiD: https://orcid.org/0000-0001-6835-0240

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Original Article

Abstract

The family Sciaenidae, commonly known as croakers or drums, represents a diverse and ecologically significant group of demersal marine and estuarine fishes found primarily in the tropical and subtropical waters worldwide. Taxonomic information on sciaenids in Indian waters remains limited since the comprehensive work of Lal Mohan (1981), who described 30 species from 14 genera. An ichthyofaunal survey conducted from 2020 to 2023 across selected marine and estuarine habitats revealed the presence of 27 sciaenid species in 14 genera (*i.e.*, *Otolithes, Johnius, Daysciaena, Kathala, Nibea, Pennahia, Otolithoides, Protonibea, Pterotolithus, Panna, Atrobucca, Chrysochir, Macrospinosa,* and *Dendrophysa*). Among the sciaenid genera, *Johnius* was the most speciose, indicating a high degree of diversification within this lineage in Indian waters. This survey provides valuable baseline data and contributes to the broader understanding of sciaenid diversity in the region.

Keywords: *Checklist, sciaenids, Arabian Sea, Bay of Bengal*

Introduction

Sciaenids (Family Sciaenidae) or croakers, comprise one of the largest families in the Order Acanthuriformes and represent one of the most ecologically and economically important groups of demersal marine fishes in tropical and temperate waters (Nelson *et al*., 2016). Globally, they have a wide distribution ranging through the temperate and tropical environments, namely from the Atlantic and Pacific oceans, the Caribbean Sea, Amazon waters, the Mediterranean Sea, and the Indo-Pacific region with high species richness reported from the Indo-west Pacific region (Nelson *et al*., 2016; Fricke *et al*., 2024). Croakers exhibit diverse external morphological features, especially in the general body form and mouth position, and this has enabled sciaenids to adapt to a wide range of habitats, from pelagic to benthic. Diverse nature is also noticed in sound production, swimbladder pattern and otolith structure, which is the most distinctive feature of the group.

Taxonomic studies on sciaenids of the Indian seas extend from classical works of Day (1888), Misra (1959), Lal Mohan (1981) to checklists by Talwar and Kacker (1984), Mohanraj *et al.* (2003). Day (1888) reported 27 species in 4 genera; Trewavas (1977) reported 75 species in 25 genera; Lal Mohan (1981) reported 36 species in 17 genera; Talwar (1995) recorded 40 species of sciaenids in 20 genera, while Mohanraj *et al.* (2003) described 30 species in 14 genera, of which 20 were commercially important. On a global pattern, Nelson *et al.* (2016) listed 283 species in 67 genera; Parenti (2020) listed 289 valid species in 69 genera. Most of the taxonomical research work was specifically done in regions of Eastern Atlantic and Indo-West Pacific by Trewavas (1962; 1977); in the Chinese waters by Chu *et al.* (1963); Western Atlantic by Chao (1978) and Japanese waters by Sasaki (1996). Globally, the production of sciaenids from capture increased from 1195939 t in 2019 to 1228260 t in 2020. Taking the pan-India fishery landings of sciaenids in 2021, 101,287 tonnes were landed, accounting for only 3.32% of the total landings.

Higher abundance and availability of sciaenids were noticed off Gujarat, Maharashtra, West Bengal, Tamil Nadu, Odisha, Andhra Pradesh, and Kerala (Bhakta *et al*., 2021). Worldwide demand for fish maw has intensified in Hong Kong and mainland China (Ben-Hasan *et al*., 2021), and recent reports of huge landings of *'koth'* across various landing centres have pointed to an increase in targeted fisheries for these species. Despite its commercial importance, studies on the diversity and taxonomy of sciaenids are scanty in India. Misidentification and synonymy have made species level assessments complicated by multiple levels of overlapping in morphometric characters from similar ecological niches (Hebert *et al*., 2003). Although recent advances in the systematics of the family Sciaenidae, particularly through molecular approaches, have improved the understanding of phylogenetic relationships *(e.g.*, Lim *et al*., 2021; Han *et al*., 2022), such studies often lack the detailed morphological validation necessary for practical species identification. In fisheries oriented and field based contexts, species recognition continues to rely predominantly on external morphology, meristic counts, and diagnostic anatomical characters. Therefore, comprehensive morphological reassessments remain indispensable for resolving taxonomic ambiguities, standardising identification keys, and validating species records.

The present study is based entirely on classical taxonomic methods, emphasising detailed morphological characters for species identification. The adopted nomenclature and classification, however, follow recent systematic updates reported in the literature. Such an approach provides a reliable framework for accurate species identification and contributes to strengthening baseline taxonomic data for Sciaenidae in Indian waters.

Material and methods

Surveys were conducted and samples collected from large and small fishing harbours on the west and east coasts of India (Fig. 1), during the period February 2020 to October 2023. A total of 656 fish samples were collected, of which 498 intact specimens were used for morphometric analysis. Croakers were sampled from small and large seines, trawls, set-barrier nets, cast nets, lift nets, traps, hooks and lines, etc. Croakers were predominantly caught in single-day trawls, multiday trawls, motorised gill nets and hooks and lines. Once collected, the fish was photographed in the field using a Canon digital camera, followed by individual tagging. The samples were then placed in crushed ice and transported to the lab in fresh condition. The fishes were then cleaned of dirt, washed to remove debris; morphometrics were done following Lal Mohan (1977) and Kumari *et al.* (2020) with slight modification. All measurements were taken using digital callipers (Mitutoyo 500-196-30-aos) in mm to the nearest 0.1 sensitivity and weighed (Saffron 2g: 3kg) to the nearest gram. The fishes were then identified using standard textbooks (Day, 1878; Trewavas, 1977; Munroe, 2000). Since the croakers are difficult to identify using external morphological characters alone, additional internal characters like dentition, arborescent appendages, and otolith were also examined and used in the species identification.

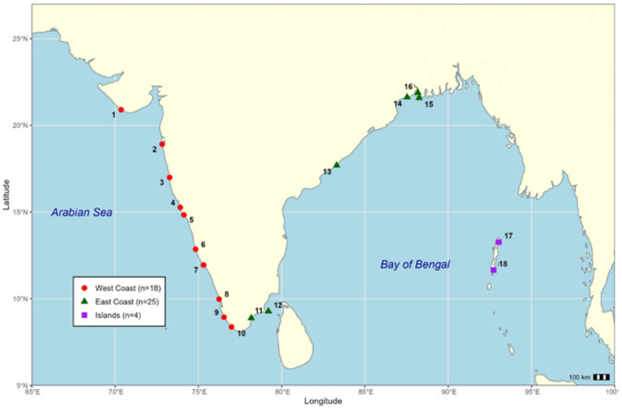


Fig. 1. Sampling locations in India 1. Veraval, 2. Mumbai, 3. Ratnagiri, 4. Benaulim, 5. Karwar, 6. Mangalore, 7. Kannur, 8. Kochi, 9. Kollam, 10. Trivandrum, 11. Tuticorin, 12. Mandapam, 13. Vishakhapatnam, 14. Digha, 15. Frazergunj, 16. Kakdwip, 17. Diglipur, 18. Port Blair

Study Area

The study was conducted across 18 strategically selected coastal locations representing the diverse marine environments of India. These sites span the eastern and western coasts, as well as the Andaman and Nicobar Islands, covering a broad geographical range from Gujarat in the northwest to West Bengal in the northeast, and extending to the islands in the Bay of Bengal. Sampling locations were selected based on ecological relevance, representation of major fishing zones, accessibility, and availability of fish landing centres. Specimens were collected primarily from landing centres and local catches, representing commercially exploited assemblages. Although a consistent methodology was followed, the spatial distribution of sampling was not entirely uniform due to logistical constraints, with relatively more dispersed coverage along the west coast and comparatively clustered sampling along parts of the east coast (Table 1).

On the west coast, sampling was carried out in Veraval (Gujarat), Mumbai and Ratnagiri (Maharashtra), Benaulim (Goa), Karwar and Mangalore (Karnataka), and four locations in Kerala, namely Kannur, Kochi, Kollam, and Trivandrum. These regions form part of the Arabian Sea coastline, characterised by estuarine systems, upwelling zones, and high marine productivity. On the east coast,

Table 1. Details of the study area where the sampling was done for the present study

No.	Collection site	State	Lat. / Long.
1.	Veraval	Gujarat	20°54′07.9″N / 70°21′52.4″E
2.	Mumbai	Maharashtra	18°54′45.5″N / 72°49′32.2″E
3.	Ratnagiri	Maharashtra	16°59′47.8″N / 73°16′26.0″E
4.	Benaulim	Goa	15°15′56.9″N / 73°54′50.4″E
5.	Karwar	Karnataka	14°50′16.2″N / 74°08′01.7″E
6.	Mangalore	Karnataka	12°51′21.5″N / 74°49′58.8″E
7.	Kannur	Kerala	11°56′40.4″N / 75°18′39.1″E
8.	Kochi	Kerala	9°58′55.6″N / 76°14′34.5″E
9.	Kollam	Kerala	8°56′19.6″N / 76°32′27.8″E
10	Trivandrum	Kerala	8°22′40.2″N / 76°59′21.0″E
11.	Tuticorin	Tamilnadu	8°53′18.3″N / 78°10′26.3″E
12.	Mandapam	Tamilnadu	9°16′48.2″N / 79°12′22.9″E
13.	Vizag	Andhra Pradesh	17°41′44.8″N / 83°18′08.8″E
14.	Digha	West Bengal	21°37′33.4″N / 87°31′55.5″E
15.	Frazergunj	West Bengal	21.5793° N / 88.2517° E
16.	Kakdwip	West Bengal	21.8760° N / 88.1853° E
17.	Port Blair	A&N Islands	13°16′08.6″N / 93°02′24.9″E
18.	Diglipur	A&N Islands	11°39′33.0″N / 92°43′31.7″E

the study included Tuticorin and Mandapam (Tamil Nadu), Visakhapatnam (Andhra Pradesh), and three locations in West Bengal, *i.e.*, Digha, Frasergunj, and Kakdwip, situated in the northern Bay of Bengal, known for its deltaic and mangrove ecosystems. Additionally, the Andaman and Nicobar Islands were represented by Diglipur and Port Blair, which support distinct island marine biodiversity.

For analytical purposes, the coastline was divided into four regions: Northwest (Gujarat–Maharashtra), Southwest (Goa–Kerala), Southeast (Tamil Nadu), and Northeast (Andhra Pradesh–West Bengal). This classification is based on geographic continuity and reflects broad differences in oceanographic and ecological characteristics, facilitating comparative analysis of species distribution patterns. The latitude and longitude range (approximately 8°N–21°N and 70°E–93°E) indicates extensive spatial coverage across Indian coastal waters.

Results and discussion

The fishes were identified using morphometric characters, otolith, dentition pattern, arborescent appendages and meristic counts. In the present work, 27 species of sciaenids in 14 genera were collected. The genera recorded were *Otolithes, Johnius, Daysciaena, Kathala, Nibea, Pennahia, Otolithoides, Protonibea, Pterotolithus, Panna, Atrobucca, Chrysochir, Macrospinosa,* and *Dendrophysa*. Of these, 8 species were reported from the northwest coast, 16 species from the southwest and 12 species from the southeast coast. Trewavas (1977) presented the taxonomic revision of the sciaenid fishes of Indo-west-Pacific seas and estuaries, wherein 65 species were placed in 27 genera and 10 tribes. A subsequent revision by Sasaki (1996) reported 47 species in 19 genera. Lal Mohan (1969), working on sciaenids in Indian waters, described 30 species in 14 genera based on the characteristic structure of air bladder, otolith and sensory pores. Lal Mohan (1981) studied 36 sciaenid species collected from Indian waters and clarified taxonomic ambiguities based on the shape of otolith, swim bladder structure and arborescent appendages. Talwar (1995) listed 40 species in 20 genera of 8 tribes from Indian waters. The different species of croakers recorded from Indian waters are described here, genus wise. The distribution pattern across both coasts and their conservation status are provided in Table 2.

Genus Otolithes Oken, 1817

Mouth large, lower jaw projecting; upper pores on snout absent; marginal pores 3–5; mental pores absent. Both jaws have canine teeth. Carrot-shaped airbladder with a series (28 to 36) of arborescent appendages along the sides, two species *Otolithes ruber* and *Otolithes cuvieri* were collected in the present study.

Otolithes ruber (Bloch and Schneider, 1801)

Common name: Tigertooth croaker (Fig. 2a)

Material examined: N=43; TL 139 mm and 210 mm Kochi (Kerala) – 12; Kollam (Kerala) – 4; Ratnagiri (Maharashtra) – 4; Goa – 5; Veraval (Gujarat) – 5; Gulf of Mannar (Tamil Nadu) – 4; Andaman-4 and Visakhapatnam (Andhra Pradesh) – 5.

Meristic characters: D IX–X, I 27-30; A II 7; P I 15; V I 5;LL 50-54; Vert. 24.

Mouth large, terminal, slightly upturned. Teeth in upper and lower jaw in two rows, inner row villiform, outer series enlarged with 1 or 2 pairs of strong canines. Caudal fin rhomboid, pointed in juveniles.

Otolithes cuvieri Trewavas, 1974

Common name: Lesser tigertoothed croaker (Fig. 2b)
Material examined: N=22; TL 152-257 mm Kochi (Kerala)–4; Kollam (Kerala)–3; Ratnagiri (Maharashtra)–3; Goa–2; Karwar (Karnataka)–3; Mangalore (Karnataka)–2; Veraval (Gujarat)–3; Kanyakumari (Tamil Nadu)–2.

Table 2. Checklist and IUCN Red List status of the sciaenids from Indian waters. IUCN Red List categories are: DD: Data Deficient, LC: Least Concern, NT: Near Threatened, VU: Vulnerable, EN: Endangered, CR: Critically Endangered

Genus	Species	West coast/state	East coast/state	IUCN
Otolithes Oken, 1817	*Otolithes ruber* (Bloch and Schneider, 1801)	Kochi (Kerala), Kollam (Kerala), Ratnagiri (Maharashtra), Goa, Veraval (Gujarat),	Gulf of Mannar (Tamil Nadu) Visakhapatnam (Andhra Pradesh)	LC
	Otolithes cuvieri (Trewavas, 1974)	Kochi (Kerala), Kollam (Kerala), Ratnagiri (Maharashtra), Goa, Karwar (Karnataka), Mangalore (Karnataka), Veraval (Gujarat)	Kanyakumari (Tamil Nadu)	LC
Daysciaena Talwar, 1970	*Daysciaena albida* (Cuvier 1830)	Kochi (Kerala)		LC
Kathala Mohan, 1969	*Kathala axillaris* Cuvier, 1830)	Kochi (Kerala), Kollam (Kerala), Mangalore (Karnataka), Goa	Kanyakumari (Tamil Nadu)	LC
Nibea Jordan and Thompson, 1911	*Nibea maculata* (Bloch and Schneider, 1801)	Kochi (Kerala), Kollam (Kerala), Karwar (Karnataka), Mangalore (Karnataka),	Visakhapatnam (Andhra Pradesh), Gulf of Mannar (Tamil Nadu)	LC
	Nibea soldado (Lacepède, 1802)		Kanyakumari (Tamil Nadu)	LC
Pennahia Fowler, 1926	*Pennahia aneus* (Bloch, 1793)	Ratnagiri (Maharashtra), Goa, Gujarat	Visakhapatnam (Andhra Pradesh), Gulf of Mannar (Tamil Nadu)	LC
	Pennahia macrocephala (Tang, 1937)		Visakhapatnam (Andhra Pradesh), Gulf of Mannar (Tamil Nadu)	LC
Otolithoides Fowler, 1933	*Otolithoides biauritus* (Cantor, 1849)	Veraval (Gujarat), Kochi (Kerala)		DD
	Otolithoides pama (Hamilton, 1822)		West Bengal	DD
Protonibea Trewavas, 1971	*Protonibea diacanthus* (Lacepède, 1802)	Mangalore (Karnataka), Goa, Gujarat	Gulf of Mannar (Tamil Nadu)	NT
Johnius Bloch, 1793	*Johnius amblycephalus* (Bleeker, 1855)	Kochi (Kerala), Kollam (Kerala), Ratnagiri (Maharashtra), Goa, Karwar (Karnataka) Mangalore (Karnataka),	Gulf of Mannar (Tamil Nadu), West Bengal	LC
	Johnius carutta (Bloch, 1793)	Kochi (Kerala), Kollam (Kerala), Mangalore (Karnataka),	Gulf of Mannar (Tamil Nadu)	LC
	Johnius carouna (Cuvier, 1830)	Kochi (Kerala), Kollam (Kerala), Ratnagiri (Maharashtra), Goa, Karwar (Karnataka)	Visakhapatnam (Andhra Pradesh)	LC
	Johnius elongatus Lal Mohan, 1976	-	Gulf of Mannar (Tamil Nadu)	DD
	Johnius belangerii (Cuvier, 1830)	Kochi (Kerala), Kollam (Kerala), Mangalore (Karnataka),	West Bengal	LC
	Johnius dussumieri (Cuvier, 1830)	Kochi (Kerala), Kollam (Kerala), Goa, Mangalore (Karnataka)	Gulf of Mannar (Tamil Nadu)	LC
	Johnius borneensis (Bleeker, 1851)	Kochi (Kerala), Kollam (Kerala)	Gulf of Mannar (Tamil Nadu), West Bengal	LC
	Johnius macrorhynus (Lal Mohan, 1976)	Kochi (Kerala)	West Bengal	LC
	Johnius macropterus (Bleeker, 1853)	Kochi (Kerala)	Gulf of Mannar (Tamil Nadu)	LC
	Johnius coitor (Hamilton, 1822)	Kochi (Kerala), Kollam (Kerala), Mangalore (Karnataka),	Gulf of Mannar (Tamil Nadu), West Bengal	LC
Dendrophysa Trewavas, 1964	*Dendrophysa russelii* (Cuvier, 1829)	Kochi (Kerala)	Gulf of Mannar (Tamil Nadu), West Bengal	LC
Chrysochir Trewavas and Yazdani, 1966	*Chrysochir aurea* (Richardson, 1846)		West Bengal	LC
Pterotolithus Fowler, 1933	*Pterotolithus maculatus* (Cuvier, 1830)		West Bengal	LC
Panna Lal Mohan, 1969	*Panna heterolepis* Trewavas, 1977		West Bengal	LC
Macrospinosa Lal Mohan, 1969	*Macrospinosa cuja* (Hamilton, 1822)		Gulf of Mannar (Tamil Nadu), West Bengal	DD
Atrobucca Chu, Lo and Wu, 1963	*Atrobucca alcocki* Talwar, 1980		Mumbai	LC

Meristic characters: D IX–X, I 27-30; A II 7; P I 15; V I 5; LL 50-52; Vert. 25.

Mouth large, terminal, lower jaw projecting, more than half of head length. Body silvery with a golden tinge on flanks; maxilla with a bluish spot, soft dorsal fin anal fin edged with grey; pectoral and pelvic fins yellow. Genus *Otolithes* has a wide distribution along both coasts. The species is commercially important and landed by trawlers.

Fig. 2. (a) *Otolithes ruber* (Bloch and Schneider, 1801) (b) *Otolithes cuvieri* Trewavas, 1974 (c) *Johnius dussumieri* (Cuvier, 1830) (d) *Johnius macropterus* (Bleeker, 1853) (e) *Johnius macrorhynus* (Lal Mohan, 1976) (f) *Johnius carouna* (Cuvier, 1830) (g) *Johnius carutta* (Bloch, 1793) and (h) *Johnius amblycephalus* (Bleeker, 1855)

Genus Johnius Bloch, 1793

This genus is represented by ten species distributed along both the east and west coasts. The species has a hammer-shaped swimbladder; but its dorsal appendages are absent; 3 pairs of mental pores. Barbels may be present or absent in some species. In *Johnius amblycephalus*, a small barbel is present on the lower jaw; the otolith has a hollow cone structure. The species recorded in the present study were in this study *J. belangerii, J. carutta, J. macropterus, J. macrorhynus, J. dussumieri, J. elongatus, J. borneensis, J. carouna, J. coitor* and *J. amblycephalus* from the southwest Bay of Bengal and eastern Arabian Sea

Johnius dussumieri (Cuvier, 1830)

Common name: Sin croaker (Fig. 2c)
Material examined: 10; Kochi (Kerala)=3, Kollam (Kerala)=3, Goa=2, Mangalore (Karnataka)=1, Gulf of Mannar (Tamil Nadu) =1.
Meristic counts: D X-XI + I 26-29; A II, 7; P I, 15-16; V I, 5. LL 49-52; Vert. 25; GR 5+8.

Body oblong to moderately compressed, dorsal profile gently arched; mouth terminal to slightly sub-terminal; fins whitish to faintly yellowish, mostly translucent; caudal fin truncated to slightly rounded. Swimbladder hammer-shaped with 14 or 15 pairs of arborescent tubules.

Johnius macropterus (Bleeker, 1853)

Common name: Large fin croaker (Fig. 2d)
Material examined: 2; TL-175-191 mm; Kochi (Kerala) =1, Gulf of Mannar (Tamil Nadu) = 1.
Meristic counts: D X + I 29-30; A II, 7; P I, 14–16; V I, 5; LL 50: Vert. 25; GR 4-5+10-11.

A small-sized species with a rounded, slightly projecting snout. Mouth narrow, inferior; lower jaw with 5 large pores, one median at base of mental barbel. Swimbladder hammer-shaped with 13 to 16 pairs of lateral appendages.

Johnius macrorhynus (Lal Mohan, 1976)

Common name: Big snout croaker (Fig. 2e)
Material examined: 35; Kochi (Kerala), West Bengal.
Meristic counts: D X-XI + I 27-29; A II, 7; P I, 15-16; V I, 5; Vert. 24; GR 4-5+7-8.

Body medium sized spindle shaped; snout rounded, projecting; eyes large. Mouth narrow, inferior; fins light yellowish to amber in colour with slightly dusky edges. Swimbladder hammer-shaped with 13 or 14 pairs of arborescent appendages.

Johnius carouna (Cuvier, 1830)

Common name: Caroun croaker (Fig. 2f)
Material examined: 22; Kochi (Kerala)=4; Kollam (Kerala)=4; Ratnagiri (Maharashtra)=4; Goa=4; Karwar (Karnataka)=3 and Visakhapatnam (Andhra Pradesh) =3.
Meristic counts: D X-XI + I 27-29; A II, 7; P I, 15-16; V I, 5; LL 48-52; Vert. 24; GR 4-5+11-12.

Body fairly deep, snout swollen and prominent, head relatively large; eyes large, spines darkened rugged; caudal fin rounded to truncate; body dark brownish grey in color. Swimbladder hammer shaped with 14 or 15 pairs of arborescent appendages.

Johnius carutta Bloch, 1793

Common name: Karut croaker (Fig. 2g)
Material examined: 32; Kochi (Kerala)=8, Kollam (Kerala) =8; Mangalore (Karnataka) =7; Gulf of Mannar (Tamil Nadu) =9.
Meristic counts: D IX–X, I 25–30; A II, 7; P I, 16; V I, 5; LL 47-50; Vert. 25; GR 3-5+7-9.

Mouth small; both jaws equipped with villiform teeth. Scales on upper part of body cycloid; caudal fin truncate; black body with a white streak present along lateral line. Swimbladder hammer-shaped, with 15 to 16 pairs of appendages.

Johnius amblycephalus (Bleeker, 1855)

Common name: Bearded croaker (Fig. 2h)
Material examined: 53; TL-78-196mm; Kochi (Kerala)-8; Kollam (Kerala)-6; Ratnagiri (Maharashtra)-7; Goa-6; Karwar (Karnataka)-7; Mangalore (Karnataka)-6; Gulf of Mannar (Tamil Nadu)-7; West Bengal-6.
Meristic counts: D X-XI + I 24-26; A II, 7; P I, 15-16; V I, 5; LL 47-52; Vert. 25; GR 4-5+6-8.

Small to medium in size, with a moderately deep body. Snout steep; bluntly rounded, mouth inferior, firm, blunt barbel present on the chin. The fish appears black with flanks black or dark brown. Swimbladder hammer shaped, with 14 to 15 pairs of appendages.

Johnius coitor (Hamilton, 1822)

Common name: Coitor croaker (Fig. 3a)
Material examined: 20; Kochi (Kerala)-6; Kollam (Kerala)-3; Mangalore (Karnataka)-3; Gulf of Mannar (Tamil Nadu)-5; West Bengal-3.
Meristic counts: D X-XI + I 26-28; A II, 7; P I, 15-16; V I, 5; LL 48-50; Vert. 25; GR 3-4+8-10.

Small sized species; snout swollen; interorbital region flat, area above the eyes with a slightly concave profile. Airbladder hammer shaped with 11 to 13 pairs of lateral appendages.

Fig. 3. (a) *Johnius coitor* (Hamilton, 1822) (b) *Johnius borneensis* (Bleeker, 1851) (c) *Johnius belangerii* (Cuvier, 1830) (d) *Johnius elongatus* Lal Mohan, 1976 (e) *Daysciaena albida* (Cuvier, 1830) (f) *Kathala axillaris* (Cuvier, 1830) (g) *Nibea maculata* (Bloch and Schneider, 1801) and (h) *Nibea soldado* (Lacepède, 1802)

Johnius borneensis (Bleeker, 1851)

Common name: Sharpnose hammer croaker (Fig. 3b)
Material examined: 12; Kochi (Kerala)-5; Kollam (Kerala)-4; Gulf of Mannar (Tamil Nadu)-2; West Bengal-1.
Meristic counts: D X-XI + I 27-30; A II 7; P I 16; V I 5; LL 46-49; Vert. 25; GR 5-6+11-13.

Body elongate, moderately compressed; dorsal profile more convex than the ventral side; body color silvery-grey colour with yellow tinge on the fins.

Johnius belangerii (Cuvier, 1830)

Common name: Belanger's croaker (Fig. 3c)
Material examined: 25; Kochi (Kerala)-7; Kollam (Kerala)-6; Mangalore (Karnataka)-6; West Bengal-6.

Meristic counts: D X-IX, I 27-31; A II, 7-8; P I, 15-16; V I, 5; Vert. 25; GR 4-5+8-11.

Mouth terminal to slightly sub terminal; snout rounded. Body silvery grey in colour, with the back appearing darker and gradually fading to a lighter underside. Head is slightly more pigmented, especially around the eyes. Swimbladder hammer-shaped with 11 to 14 pairs of arborescent appendages.

Johnius elongatus Lal Mohan, 1976

Common name: Spindle croaker (Fig. 3d)
Material examined: 30; Gulf of Mannar (Tamil Nadu).
Meristic counts: D X-XI + I 24-29; A II, 7; P 17; V I, 5; LL 49-51; Vert. 25; GR 4-5+7-10.

Body moderately elongate, laterally compressed; head large; snout blunt; preopercular edge appears slightly serrated; dorsal fin long, continuous; caudal fin rounded to truncate.

Genus *Daysciaena* Talwar 1970

The genus is represented by one species *Daysciaena albida,* which was collected from the west coast (Kerala). Mouth terminal. Snout with 3 upper and 5 marginal pores; mental pores 5, of which the median is the opening of a pair lying close together behind the symphysis; a pair of minute barbels present between the median and anterior lateral pores, second anal spine strong. Swimbladder carrot-shaped, extending behind the vent to the anal spines.

Daysciaena albida (Cuvier, 1830)

Common name: Two-bearded croaker (Fig. 3e)
Material examined: N= 44; TL 210-566 mm from Kalamukku.
Meristic counts: DIX-X + 123-26; A II, 7; P I, 17; V I, 5; LL 45-58; Vert. 24; GR 11-12/20-22.

Body oblong; snout rounded, projecting only slightly beyond tip of upper jaw; mouth terminal. Teeth differentiated in size in both jaws, outer row of upper and inner posterior teeth of lower jaw enlarged, spaced; canines absent. Swimbladder carrot shaped, extending behind the vent to the anal spines, with 17 to 19 pairs of arborescent appendages. Body greyish on back silvery on belly; pectoral, pelvic and caudal fins yellowish; a black blotch present at axil of pectoral fin. The fish was collected from Vembanad Lake west coast (Kerala) and is commercially important species.

Genus Kathala Lal Mohan, 1969

Mouth terminal, jaws about equal; snout with small pores; 3 mental pores; swimbladder carrot shaped with unbranched cornua entering the head. Caudal fin rhomboid. The genus is monotypic, species easily identified by a small black spot at and above the pectoral fin base region. *Kathala axillaris* was collected during the study from both east and west coasts of India.

Kathala axillaris (Cuvier, 1830)

Common name: Kathala croaker (Fig. 3f)
Material examined: N=15; TL 120-154 mm Kochi (Kerala)-5; Kollam (Kerala)-3; Mangalore (Karnataka)-3; Goa-2; Kanyakumari (Tamil Nadu)-2.
Meristic counts: D X I, 27-29; P 18; V I, 5; A II, 7; LL 45-50; Vert. 25; GR (9-12) + (19-23).

Medium sized with a fairly deep body. Snout rounded, but not projecting. Mouth terminal and oblique; jaws nearly equal. Caudal fin rhomboid. Body colour is silvery grey to bluish-grey on the back, fading to silvery white on the belly; body with a black notch on the base of pectoral fin. *Kathala axillaris* is a commercially important fish in the fishery.

Genus Nibea Jordan and Thompson, 1911

Species in this genus are distinguished by a slightly projecting snout; five mental pores surrounded by thick skin; mouth terminal; teeth differentiated in size in both jaws, inner row of lower jaw and outer row of upper jaw with enlarged teeth; barbels absent; swimbladder carrot-shaped. Worldwide, ten species are reported, and in the present study two species were recorded, namely *Nibea maculata* and *Nibea soldado*. In fresh condition, *Nibea maculata* is easily distinguished by having five dark blotches, which may be broken or entire, extending from the dorsum to the lower part of the flanks. In the case of *Nibea soldado*, a well-arched back with deep body. Both *Nibea maculata* and *Nibea soldado* are commercially important fish.

Nibea maculata (Bloch and Schneider, 1801)

Common name: Blotched croaker (Fig. 3g)
Material examined: 37; TL-128-215 mm; Kochi (Kerala)-7; Kollam (Kerala)-6; Karwar (Karnataka)-6; Mangalore (Karnataka)-6; Visakhapatnam (Andhra Pradesh)-6; Gulf of Mannar (Tamil Nadu)-6.
Meristic counts: D X + I 24-26; A II, 7; P I, 17; V I, 5; LL 45-47; Vert. 45; GR 5-6+7-8.

Mouth inferior; lips thick; upper jaw overshooting lower and extending to below middle of eye; mental pores 5, surrounded by thick skin. Swimbladder carrot-shaped, with 18 to 21 pairs of arborescent appendages. The fish has a wide distribution on both east and west coast.

Nibea soldado (Lacepède, 1802)

Common name: Soldier croaker (Fig. 3h)
Material examined: 3; TL-175-191 mm; Tamil Nadu.

Meristic counts: D X + I 28-29; A II, 7; P I, 16; V I, 5; LL 47-49; Vert. 45; GR 4-5+7-8.

Mouth terminal; snout blunt, not projecting beyond upper jaw, jaws meeting equally in front; five mental pores; median composed of two united by a crescentric groove just behind symphysis. Swimbladder carrot-shaped with 20 to 22 pairs of lateral appendages.

Genus Pennahia Fowler, 1926

Mouth large, terminal; lower jaw half as long as head or more. Teeth well differentiated in size in both jaws, canine teeth present; Swimbladder carrot-shaped with 17 to 27 pairs of arborescent appendages along sides of bladder. Two species *Pennahia aneus* and *Pennahia macrocephala,* were collected in the present study. *Pennahia aneus* is a commercially important fish on the east coast of India.

Pennahia aneus (Bloch, 1793)

Common name: Bigeye croaker (Fig. 4a)
Material examined: N=21; TL 111-175mm Ratnagiri (Maharashtra)-5; Goa-3; Gujarat-4; Visakhapatnam (Andhra Pradesh)-2; Gulf of Mannar (Tamil Nadu)-4 and Andaman-3.
Meristic counts: D IX-X + I, 21-26; A II, 7-8; P 16-17; V I, 5; LL 52–54; Vert. 26; GR 5–6 + 9–11.

Deep bodied species with large, terminal, oblique mouth; upper jaw reaching below the hind part of the eye; lower jaw projecting when the mouth is open. Two pairs of small mental pores present, with the anterior pair located at the front of the prominent chin.

Pennahia macrocephalus (Tang, 1937)

Common name: Big-head pennah croaker (Fig. 4b)
Material examined: N=7; TL 132-205mm Visakhapatnam (Andhra Pradesh)-2; Gulf of Mannar (Tamil Nadu)-5.
Meristic counts: D X + I 24-26; A II, 7; P 17; V I, 5; LL 45-49; Vert. 26; GR 4-6/10-12.

A medium sized species, with an acute prominent snout which slightly projects beyond upper jaw. Mouth inferior; lips rather thick. Mental pores 5; surrounded by thick skin. Swimbladder carrot shaped, with 18 to 21 pairs of arborescent appendages.

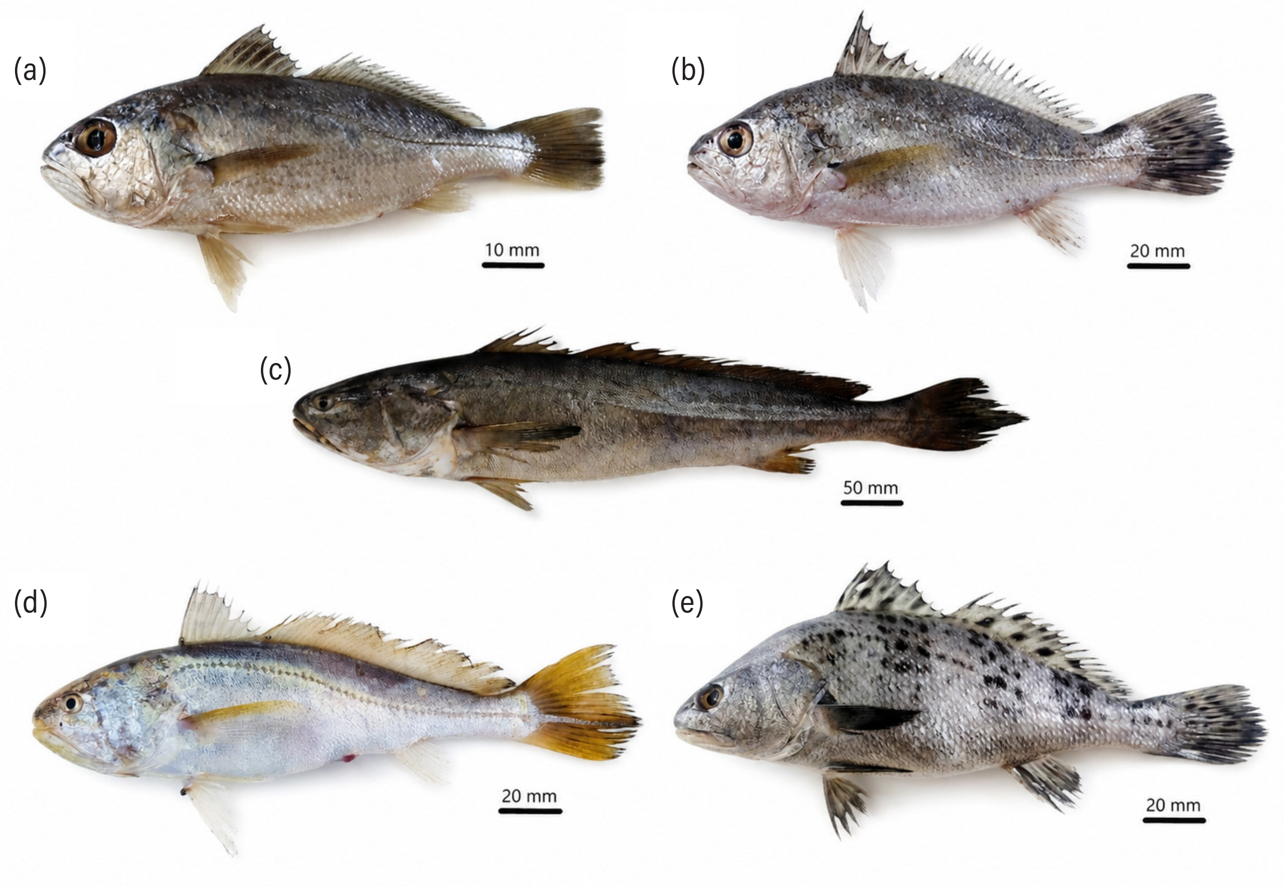


Fig. 4. (a) *Pennahia anea* (Bloch, 1793) (b) *Pennahia macrocephalus* (Tang, 1937) (c) *Otolithoides biauritus* (Cantor, 1849) (d) *Otolithoides pama* (Hamilton, 1822) and (e) *Protonibea diacanthus* (Lacepède, 1802)

Genus Otolithoides Fowler, 1933

Mouth large terminal; teeth well differentiated in size in both jaws, upper outer row and lower inner row caniniform, spaced. Swimbladder carrot shaped with a pair of long tubular appendages originating near its posterior end. The second anal spine weak. Lateral line scales cycloid, covered with small subsidiary scales; scales of upper anterior part of body very small. In the present study two species *Otolithoides biauritus* and *Otolithoides pama* were collected.

Otolithoides biauritus (Cantor, 1849)

Common name: Bronze croaker (Fig. 4c)
Material examined: 8; TL-120-292 mm, Veraval (Gujarat) = 7, Kochi (Kerala) = 1.
Meristic counts: D IX + I, 28-29; A II, 8; P I, 17; V I, 5; LL 57-58; Vert. 82; GR 7-11.

A large species with a slender body and acute snout. Mouth terminal; upper jaw reaching back well beyond eye. Scales small. Caudal fin acutely pointed. Swimbladder carrot shaped, with a single pair of long tubular appendages arising from posterior end of bladder. *O. biauritus*, known for its large size and firm flesh, is especially valued in local markets and is landed as a high-value species. The swim bladders of large fishes are harvested for export, adding to their commercial value.

Otolithoides pama (Hamilton, 1822)

Common name: Bronze croaker (Fig. 4d)
Material examined: 15; TL 145-223 mm from West Bengal.
Meristic counts: D X + I 42-43; A II, 7; P I, 16; V I, 5; LL 56-58, Vert. 25; GR 5+12.

Body slender; snout acute; mouth large and terminal; eyes very small; interorbital region broad, conical. Fins yellowish, the upper half of dorsal fin grey. Swimbladder carrot-shaped with a pair of tubule originating near its posterior end and extending forwards into head, with several branches. *O. pama*, though small in size, also contributes significantly to artisanal and small scale fisheries. Both *Otolithoides biauritus* (Cantor, 1849) and *Otolithoides pama* (Hamilton, 1822) are of high commercial importance, particularly in the coastal fisheries of the eastern coast, including West Bengal, Odisha, Andhra Pradesh, and Tamil Nadu.

Genus Protonibea Trewavas, 1971

Head large; snout acute shaped; mouth large, terminal; three pairs of mental pores; swimbladder carrot shaped; caudal fin rhomboid; teeth well differentiated in both jaws. The species is characterised by small black spots on the upper part of the body, including the dorsal and caudal fins. The genus is represented by a single species *Protonibea diacanthus*, which is highly valued in export. Large sized fishes are worth lakhs, and their air bladder fetches a prime value in export.

Protonibea diacanthus (Lacepède, 1802)

Common name: Spotted croaker (Fig. 4e)
Material examined: N=5 from Karnataka = 1; Goa = 1; Gujarat = 1; Mandapam Harbour = 1; Kochi = 1.
Meristic counts: D IX-X + I 22-25; A II, 7; P I, 17-18; V I, 5, LL 49-53, Vert. 25; GR 4-5+ 6-8.

Large, slender bodied; mouth large, body dark grey; five dark blotches along back, many smaller black spots (about size of pupil) on top of head, upper half of body, dorsal and caudal fins; pectoral, pelvic, anal and lower parts of caudal fins black. Swimbladder carrot-shaped bearing 16 to 20 pairs of appendages. It is one of the largest sciaenid species found in Indian coastal and estuarine waters, and is highly valued for both its meat and swim bladder. The flesh is considered nutritious and is widely consumed, especially in eastern coastal states like Andhra Pradesh, Odisha, and West Bengal, where it supports local livelihoods through small-scale and commercial fisheries. The species is typically caught using trawl nets, gill nets, and hook-and-line. Fishery for this species is present along Gujarat coast.

Genus Dendrophysa Trewavas, 1964

Head small; mouth inferior; snout prominent lower jaw shorter than upper. A median mental barbel present; five mental pores, the median of which is the aperture of a pair that are situated closely below the symphysis. Teeth in upper jaw villiform band, outer row slightly enlarged; teeth of lower jaw small uniform. Monotypic genus.

Dendrophysa russelii (Cuvier, 1829)

Common name: Goatee croaker (Fig. 5a)
Material examined: 17; TL 115-178 mm, Kochi (Kerala) -4, Gulf of Mannar (Tamil Nadu)- 5, West Bengal- 3, Andaman-3, Gujarat -2.
Meristic counts: D X + I 25-32; A II, 7; P 16; V I, 5; LL 46-49; Vert. 24; GR 4-5+7-8.

Small-sized body oblong; head small, inferior mouth. Snout rounded; projecting slightly before upper jaw. Mental pores 5, one median, two lateral pairs; one pointed and tapering barbel behind the median mental pore. Swimbladder carrot-shaped with 14 to 17 pairs of arborescent diverticula. The fish has moderate commercial importance in India, particularly along the east coast, including the coastal waters of Andhra Pradesh, Odisha, and Tamil Nadu.

Genus *Chrysochir* Trewavas and Yazdani, 1966

Mouth terminal, or slightly inferior; upper jaw slightly protruded than lower jaw; snout with 3 upper and 5 marginal pores; mental pores 5; second anal spine strong; carrot-shaped swimbladder extending behind the vent to the anal spines. A single species *Chrysochir aurea* (Richardson, 1846) was collected in the present study.

Chrysochir aurea (Richardson, 1846)

Common name: Reeve's croaker (Fig. 5b)
Material examined: N = 8; TL 152-245 mm from West Bengal.
Meristic counts: D X + I 26-28; A II, 6-7; P I, 17; V I, 5; LL 49-52; Vert. 26; GR 5-9.

Body slender, with an acute, prominent snout. Mouth large; caudal fin rhomboid with pointed tip. Swimbladder carrot-shaped, bearing 24 to 28 pairs of arborescent appendages along sides. The fish has high commercial importance in parts of its range, including Indian coastal waters, particularly in the Bay of Bengal region. In India, it is landed primarily found along the east coast, including Andhra Pradesh, West Bengal, and Odisha.

Genus Pterotolithus Fowler, 1933

Body elongate, compressed; mouth large; strongly oblique. A pair of canine teeth in each jaw. No upper pores on snout; body with a distinctive pattern of three to four rows of black blotches on the upper part of the body. A single species *Pterotolithus maculatus* (Cuvier, 1830) was collected in the present study.

Pterotolithus maculatus (Cuvier, 1830)

Common name: Blotched tiger-toothed croaker (Fig. 5c)
Material examined: N=3; 148-170 mm from West Bengal.
Meristic counts: D IX + I 30-34; A II, 10; P I, 17; V I, 5; LL 48-49; Vert. 25; GR 7+8.

Body large, slender; with the head profile low and horizontal. Mouth large, oblique, superior, with a distinctive pattern of three or four rows of black blotches on the upper part of the body. Swimbladder broad, oval, with a narrow point posteriorly, having 37 to 42 pairs of arborescent appendages. The fish is not commercially important in the Indo-West Pacific region, including the east coast of India. It is commonly found in coastal and estuarine waters, where it contributes to the artisanal and small-scale fisheries, particularly in states like West Bengal and Odisha.

Genus Panna Lal Mohan, 1969

Fishes of this genus have a carrot shaped swimbladder with an anterior tubule on each side, which bifurcates into a long, simple abdominal appendage and a simple or branched cephalic appendage. Mouth large, terminal; teeth well differentiated in size in both jaws; moderately spaced, and a narrow band of small inner teeth; 3 pairs of mental pores. In the present study, *Panna heterolepis* Trewavas, 1977 was obtained. The species was collected from West Bengal.

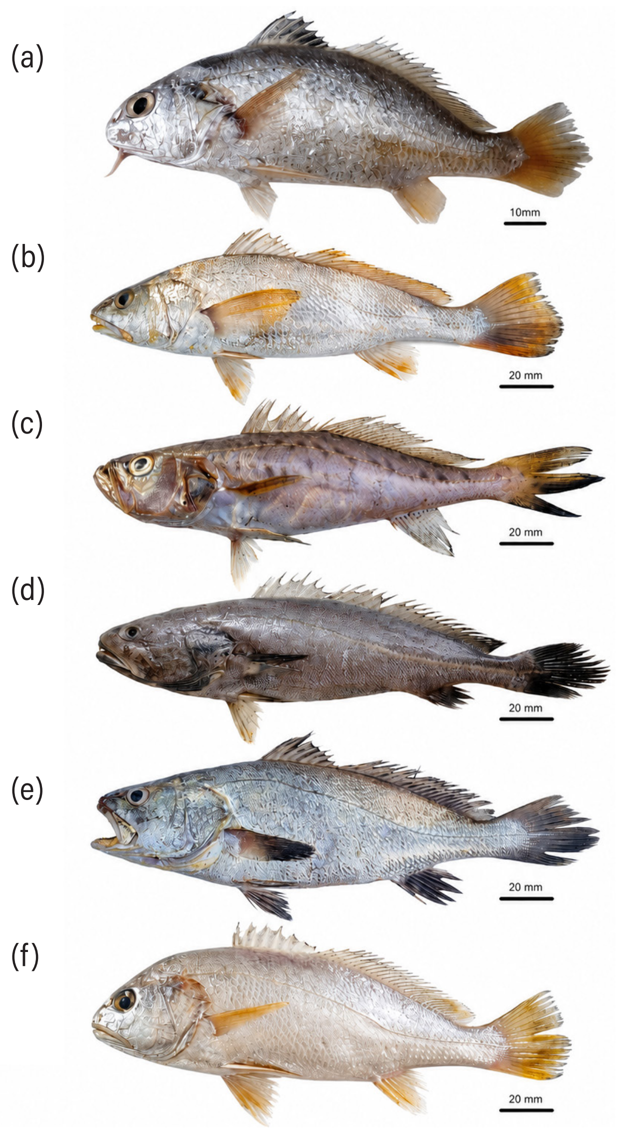


Fig. 5. (a) *Dendrophysa russelii* (Cuvier, 1829) (b) *Chrysochir aurea* (Richardson, 1846) (c) *Pterotolithus maculatus* (Cuvier, 1830) (d) *Panna heterolepis* Trewavas, 1977 (e) *Atrobucca alcocki* Talwar, 1980 and (f) *Macrospinosa cuja* (Hamilton, 1822)

Panna heterolepis Trewavas, 1977

Common name: Hooghly croaker (Fig. 5d)
Material examined: 1 TL=160 mm from West Bengal.
Meristic counts: D IX, I 34; A II, 7; P I, 16-17; V I, 5; LL 54; Vert. 24; GR 6+12.

Body medium, slender. Head compressed with an acute snout. Mental pores three pairs, anterior very small, on front of chin, second and third pair of pores open ovals. No pores on snout. Body brownish, becomes lighter on flanks and belly. Swimbladder carrot shaped, with a diverticulum on each side arising from the anterior end and immediately dividing into a short abdominal and a narrower, unbranched cephalic tube.

Genus Atrobucca Chu, Lo and Wu, 1963

Mouth terminal; teeth sharp, needle-like, well differentiated in size in both jaws, outer series in upper jaw and inner series in lower jaw enlarged and spaced, canines absent; carrot shaped swimbladder with 20 to 30 pairs of lateral arborescent appendages; three pairs of mental pores on lower jaw; anterior pair minute and on front of chin, separated by symphysis. In the present study, *Atrobucca alcocki* Talwar, 1980 was collected from Mumbai.

Atrobucca alcocki Talwar, 1980

Common name: Bombay blackmouth croaker (Fig. 5e)
Material examined: N = 4; TL 150 – 204 mm from Mumbai.
Meristic counts: D X, I 2-26; A II, 7, P I, 16-17; V I, 5; LL 49-50; Vert. 25; GR 5-8.

Mouth terminal; teeth well differentiated in both jaws; outer upper row enlarged, moderately spaced, with a narrow band of small inner teeth. The mouth is black in colour. This species is not as well known or abundant in shallow coastal fisheries as some other sciaenids, and is occasionally encountered in deep-sea trawl fisheries.

Genus Macrospinosa Lal Mohan, 1969

Mouth terminal, lower jaw slightly inferior; teeth differentiated in size in both jaws, but without specialised caniniform teeth. Snout with three indistinct pores, five well developed pores at the edge of the rostral flap; mental pores three pairs, those of the anterior pair immediately behind the symphysis. Second anal fin spine long, robust. In the present study, *Macrospinosa cuja* (Hamilton, 1822) was collected from West Bengal.

Macrospinosa cuja (Hamilton, 1822)

Common name: Cuja bola (Fig. 5f)
Material examined: 1 TL=218 mm from West Bengal.
Meristic counts: D X, I 27-29; A II, 7; P 17; V I, 5;LL 50;Vert. 26; GR 5 + 7.

A fairly large species with a blunt snout; dorsal profile above the orbit is convex. Dorsal fin deeply notched. Mental pores three pairs, the anterior pair immediately behind the symphysis close together or in a pit opening by a single pore. Swimbladder carrot-shaped. Though not a high value species, it is frequently caught as part of the multispecies demersal fishery, especially in Odisha and West Bengal.

The west coast exhibits the highest species diversity and supports a rich diversity of sciaenid species. Genus *Johnius* exhibits the highest species richness, with six species (e.g., *J. amblycephalus, J. carutta, J. carouna, J. belangerii, J. dussumieri*) distributed widely along the west coast. The east coast supports fewer species in terms of overall richness but includes significant representatives from multiple genera, such as *Otolithes ruber, Nibea maculata, Pennahia macrocephala, Protonibea diacanthus,* and *Dendrophysa russelii*. Notably, the Gulf of Mannar (Tamil Nadu) and West Bengal emerge as prominent localities with a high occurrence of croaker species. Several genera like *Pterotolithus, Panna, Macrospinosa*, and *Atrobucca* are restricted to only the east coast (Orissa and West Bengal) region, indicating a more localised distribution.

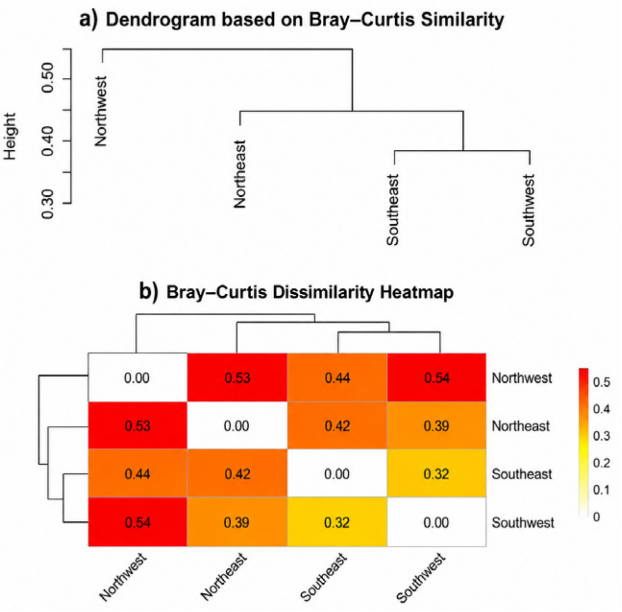
Multivariate statistical analysis of sciaenids

The dendrogram constructed using the Bray–Curtis similarity index reveals distinct patterns in the distribution of sciaenid (croaker) species across the coastal regions of India (Fig. 6a). The northwest coast forms an isolated cluster, diverging at the highest hierarchical level, indicating a comparatively low similarity in species composition with the other regions. This distinctiveness may be attributed to region specific ecological conditions or the presence of locally restricted species. The northeast coast exhibits an intermediate level of similarity, forming a separate cluster that is moderately related to the southern regions, yet still distinct in its species composition. In contrast, the southeast and southwest coasts cluster closely together at the lowest height, signifying a high degree of similarity in sciaenid species assemblages. This close association likely reflects shared ecological and environmental conditions, as well as potential continuity in habitat types across these southern maritime states. Overall, the hierarchical clustering analysis highlights clear biogeographic structuring in the distribution of sciaenids along the Indian coastline, underscoring the relative faunal distinctiveness of the northern regions and the species homogeneity of the southern coastal zones.

The Bray-Curtis dissimilarity heatmap provides a quantitative assessment of the variation in sciaenid (croaker) species composition across four major coastal regions of India–northwest, northeast, southeast, and southwest (Fig. 6b). The observed dissimilarity values range from 0.32 to 0.54, where higher values indicate greater dissimilarity in species assemblages. Notably, the Northwest coast exhibits the highest levels of dissimilarity with the other regions, particularly with the Southwest (0.54) and Northeast (0.53), suggesting that it harbours a distinct croaker community structure, likely influenced by unique environmental or oceanographic conditions. In contrast, the southeast and southwest coasts display the lowest dissimilarity value (0.32), indicating a high degree of similarity in their species composition. This pattern implies a strong biogeographic affinity between these two southern regions, possibly due to continuous habitat features or similar ecological niches. The northeast coast shows moderate dissimilarity with both the southeast (0.42) and southwest (0.39), reflecting an intermediate faunal relationship.

The associated dendrogram confirms these findings, grouping southeast and southwest as the most similar regions, followed by the northeast, while the northwest forms a separate cluster. Collectively, these results underscore a distinct latitudinal gradient in sciaenid species distribution along the Indian coastline, with southern regions showing higher faunal connectivity and the northwest emerging as a biogeographically isolated zone. Such insights are critical for regional biodiversity assessments, conservation prioritisation, and understanding ecological drivers influencing species turnover among India's coastal ecosystems.

Presently, 270 species in 70 genera are reported throughout the world in the family Sciaenidae (Chao, 1986). Allen and Robertson (1994) estimated 80 genera with about 300 species. Trewavas (1977) grouped 65 species into 27 genera in 10 tribes. Lal Mohan (1981) recorded 36 species from 14 genera, from which we have collected 15 species under 7 genera. Talwar (1995) reported 40 species from 20 genera in 8 tribes, from which we have collected 17 species in 8 genera (Table 2). Most work has been limited to regional studies (*viz*., eastern Atlantic by Trewavas, 1962; Chinese waters by Chu *et al*., 1963; Indian waters by Mohan, 1972; Indo- West Pacific by Trewavas, 1977; western Atlantic by Chao, 1978). In the present study, based on morphometric and hard parts, we could identify 27 species in 14 genera from the Indian coasts. Weber and Beaufort (1936) recorded 34 species from 6 genera from the Indo-Australian Archipelago. Allen and Robertson (1994) estimated 80 genera with about 300 species. Druzhinin (1971) recorded 45 species from 15 genera, while 48 species in 27 genera were reported by Lal Mohan (1991) from the Indian Ocean.


a) Dendrogram based on Bray–Curtis Similarity

b) Bray–Curtis Dissimilarity Heatmap

	Northwest	Northeast	Southeast	Southwest
Northwest	0.00	0.53	0.44	0.54
Northeast	0.53	0.00	0.42	0.39
Southeast	0.44	0.42	0.00	0.32
Southwest	0.54	0.39	0.32	0.00

Fig. 6. Distribution of sciaenids from the different coasts of India based on Bray-Curtis Similarity Index: (a) dendrogram representing Bray-Curtis similarity, (b) heatmap ordination representing clustering of coasts

Lal Mohan (1981) in his consolidated work had reported 36 species in 14 genera. The comparative assessment between the species listed by Lal Mohan (1981) and those validated in the present study reveals both taxonomic advancements and shifts in species status and occurrence in Indian waters. Several species originally identified by Lal Mohan have undergone nomenclatural changes or genus level reassignments based on modern taxonomic frameworks. *Umbrina canariensis* described by Lal Mohan (1981), is of doubtful occurrence had included some doubtful species and some species not recorded from Indian waters.

Several species appear consistently across all references and were also confirmed in the present study, indicating their continued prevalence and ecological stability in Indian marine ecosystems. These include commonly encountered species such as *Kathala axillaris*, *Otolithoides biauritus*, *Otolithoides pama*, *Chrysochir aurea*, *Otolithes ruber*, *Otolithes cuvieri*, *Pterotolithus maculatus*, and *Protonibea diacanthus*. Their consistent documentation across nearly a century affirms their status as core sciaenid species in the region. Conversely, some taxa such as *Bahaba chaptis, Macrospinosa cuja, Panna hetrolepis, Atrobucca nibe, Nibea chui, Johnius macropterus*, and *Johnius mannarensis* are categorised as rare or of uncertain status, possibly due to habitat specificity, depth distribution, limited population sizes, or under sampling. Notably, *Argyrosomus hololepidotus*, though previously mentioned in older literature, is clarified in this table as a South African species not found in Indian waters, pointing to earlier misidentifications or range misinterpretations.

Table 3. Observations done by various workers on the species of the family Sciaenidae

Genus	Lal Mohan, 1981	Current valid name	Weber and Beaufort (1936)	Trewavas (1977)	Talwar (1995)	Present study	Comments
Umbrina	*Umbrina sinuata*	*Umbrina canariensis*		✓	✓		Doubtful
Bahaba	*Bahaba chaptis*	*Bahaba chaptis*		✓	✓		Rare occurrence
Macrospinosa	*Macrospinosa cuja*	*Macrospinosa cuja*		✓	✓	✓	Rare occurrence
Kathala	*Kathala axillaris*	*Kathala axillaris*	✓	✓	✓	✓	Common
Otolithoides	*Otolithoides biauritus*	*Otolithoides biauritus*	✓	✓	✓	✓	Common
	Otolithoides pama	*Otolithoides pama*	✓	✓		✓	Common
Panna	*Panna microdon*	*Panna microdon*	✓	✓	✓		Doubtful
		Panna hetrolepis		✓	✓	✓	Rare
Pennahia	*Pennahia macrophthalamus*	*Pennahia aneus*	✓	✓	✓	✓	Common
		Pennahia macrocephala		✓	✓	✓	Rare
Argyrosomus	*Argyrosomus hololepidotus*	*Argyrosomus hololepidotus*		✓	✓		Not found in India. It is a South African species
	Argyrosomus amoyensis	*Argyrosomus amoyensis*		✓	✓		Doubtful
Atrobucca	*Atrobucca nibe*	*Atrobucca nibe*		✓	✓		Rare
	Atrobucca trewavasae	*Atrobucca trewavasae*		✓	✓		Occasional
		Atrobucca alcocki		✓	✓	✓	Occasional
Chrysochir	*Chrysochir aureus*	*Chrysochir aurea*		✓	✓	✓	Common
Otolithes	*Otolithes ruber*	*Otolithes ruber*	✓	✓	✓	✓	Common
	Otolithes cuvieri	*Otolithes cuvieri*		✓	✓	✓	Common
Pterotolithus	*Pterotolithus maculatus*	*Pterotolithus maculatus*	✓	✓	✓	✓	Common
Protonibea	*Protonibea diacanthus*	*Protonibea diacanthus*	✓	✓	✓	✓	Common
Dendrophysa	*Dendrophysa russelii*	*Dendrophysa russelii*	✓	✓	✓	✓	Occasional
Nibea	*Nibea semiluctuosa*	*Paranibea semiluctuosa*		✓			Rare
	Nibea albida	*Daysciaena albida*		✓	✓	✓	Common
	Nibea maculata	*Nibea maculata*	✓	✓	✓	✓	Occasional
	Nibea chui	*Nibea chui*		✓	✓		Rare
	Nibea soldado	*Nibea soldado*	✓	✓	✓	✓	Occasional
Johnius	*Johnius carutta*	*Johnius carutta*	✓	✓	✓	✓	Occasional
	Johnius elongatus	*Johnius elongatus*		✓	✓	✓	Occasional
	Johnius belangerii	*Johnius belangerii*	✓	✓	✓	✓	Common
	Johnius dussumieri	*Johnius dussumieri*	✓		✓	✓	Common
	Johnius mannarensis	*Johnius mannarensis*					Rare
	Johnius coitor	*Johnius coitor*		✓	✓	✓	Occasional
	Johnius glaucus	*Johnius carouna*			✓	✓	Common
	Johnius macropterus	*Johnius macropterus*	✓	✓	✓	✓	Rare
		Johnius amblycephalus		✓	✓	✓	Common
Johnieops	*Johnieops marorhynus*	*Johnius macrorhynus*		✓	✓	✓	Common
	Johnieops aneus	*Pennahia aneus*		✓	✓	✓	Common
	Johnieops dussumieri	*Johnius dussumieri*			✓	✓	Common
	Johnieops sina	*Johnius dussumieri*			✓	✓	Common
	Johnieops vogleri	*Johnius borneensis*	✓		✓	✓	Common

Certain species, such as *Atrobucca alcocki, Dendrophysa russelii, Nibea soldado, Johnius elongatus,* and *Johnius coitor* are marked as "occasional," indicating they may be locally abundant but have patchy or seasonal distributions. The presence of several revalidated or recently confirmed species, like *Johnius amblycephalus*, *Johnius borneensis* (formerly *Johnieops vogleri*), and the synonymised *Johnius dussumieri* (previously listed under *Johnieops*), demonstrates the impact of modern revisions in taxonomy. Lal Mohan (1991) has reported the sciaenid fishery along the four major coastal regions of India, *i.e.*, northwest, southwest, southeast, and northeast, with significant variation in species diversity. The northwest coast

Table 4. Number of species recorded from different Coastal regions of India

No.	Genus	Total no. of Species	Northeast	Northwest	Southeast	Southwest
1	*Otolithes*	2	2	2	2	2
2	*Daysciaena*	1	0	0	0	1
3	*Kathala*	1	1	1	1	1
4	*Nibea*	2	1	1	2	1
5	*Pennahia*	2	1	1	2	0
6	*Otolithoides*	2	2	1	0	0
7	*Protonibea*	1	1	1	1	1
8	*Johnius*	10	8	10	9	9
9	*Dendrophysa*	1	1	1	1	1
10	*Chrysochir*	1	1	0	0	0
11	*Pterotolithus*	1	1	0	0	0
12	*Panna*	1	1	0	0	0
13	*Macrospinosa*	1	1	0	0	0
14	*Atrobucca*	1	0	1	0	0

stands out as one of the richest regions for sciaenid resources, with a high diversity and dominance of species such as *Otolithes cuvieri*, *Johnius glaucus* and *Protonibea diacanthus*. The southwest coast, while supporting a moderately diverse sciaenid assemblage, is primarily characterised by species like *Johnius macrorhynus*, *J. aneus*, and *O. cuvieri*. The southeast coast hosts a broader and more evenly distributed range of species, including *Pennahia macrocephalus*, *Johnius carutta*, *Kathala axillaris*, and *Chrysochir aurea*, contributing to a productive and diverse fishery. The northeast coast reflects a rich sciaenid fauna with notable contributions from *P. macrocephalus*, *C. aureus*, *Johnius coitor*, and *Otolithoides pama*. The present study matches these results that the rich sciaenid ground on the northwest coast of India.

The distribution of Sciaenidae species along the Indian coastline reflects significant regional variation in species richness and composition. The northwest coast hosts the highest diversity, with a dominance of important genera such as *Johnius, Otolithes, Nibea, Protonibea,* and *Otolithoides*, indicating highly favourable conditions for croakers. The southwest coast also supports a rich sciaenid community, with many overlapping genera including *Johnius, Otolithes, Nibea*, and *Atrobucca*, highlighting the ecological productivity of this region. On the southeast coast, sciaenid diversity is moderate, with prominent genera including *Johnius, Pennahia, Chrysochir, Dendrophysa,* and *Kathala*. These species are well adapted to the sandy and muddy bottoms of the continental shelf in this region. The northeast coast, while relatively lower in diversity, features distinct genera such as *Macrospinosa, Otolithoides, Bahaba, Pterotolithus, Johnius* and *Pennahia*, often associated with coastal ecosystems.

Overall, the west coast (northwest and southwest) stands out as the most species rich zone for sciaenids, dominated by key genera like *Johnius, Otolithes*, and *Nibea*. The East Coast (southeast and northeast), though less diverse, supports several region-specific genera contributing to localised fisheries. The taxonomy of Sciaenidae has shifted from classical morphology based identification to a more rigorous, integrative taxonomic approach incorporating molecular phylogenetics. While early taxonomists laid the foundation, recent work has revealed the non monophyly of several genera and the need for comprehensive global revisions. As molecular data continue to grow, further changes in genus boundaries and species identities are expected, especially in species-rich tropical Indo-Pacific regions.

The present study provides an updated account of the diversity and distribution of sciaenids (Family Sciaenidae) in Indian waters based on detailed morphological examination. Although no new species records were observed, the study verifies the occurrence of previously reported taxa and refines species identification, addressing challenges of misidentification and overlapping morphometric characters. The species composition largely agrees with earlier reports (Day, 1888; Trewavas, 1977; Lal Mohan, 1981; Talwar, 1995; Mohanraj *et al*., 2003), with minor variations that may be attributed to differences in sampling, fishing pressure, and environmental conditions. As demersal fishes associated with soft bottom habitats, sciaenids show distribution patterns influenced by substrate type, depth, and estuarine inputs (Chao, 1978; Sasaki, 1996). The observed similarity in species composition along the southern coast of India can be explained by continuity of habitats, comparable environmental conditions, and uniform fishing practices, particularly along Kerala and Tamil Nadu coasts (Qasim, 1977; CMFRI, 2020). From a fisheries perspective, sciaenids are economically important, and increasing demand for fish maw may influence exploitation patterns and species composition (FAO, 2020; Ben-Hasan *et al*., 2021; CMFRI, 2021). Environmental factors such as seasonal variability, freshwater influx, and climate-related changes may also affect distribution and abundance (Pauly and Christensen, 1995; Legg, 2021). Despite advances in molecular systematics, species identification in fisheries contexts continues to rely primarily on morphology (Nelson *et al*., 2016; Parenti, 2020), and thus the present classical taxonomic approach provides essential baseline data for accurate identification, biodiversity assessment, and sustainable fisheries management.

Conclusion

This study provides an updated and comprehensive assessment of the diversity, distribution, and biogeographic patterns of sciaenid fishes along the Indian coastline and associated island ecosystems. Clear regional structuring of sciaenid assemblages was observed, with higher similarity between the southwest and southeast coasts and a distinct faunal composition along the northwest coast, reflecting the influence of oceanographic processes, shelf characteristics, and habitat variability. Island ecosystems, although supporting lower species richness, contribute to regional diversity and highlight the importance of insular habitats in sciaenid distribution. The results further emphasise the growing vulnerability of several sciaenid species under increasing fishery pressure, particularly large-bodied and high-value taxa targeted for fish maw trade. The presence of Data Deficient and Near Threatened species within commercially exploited assemblages underscores significant gaps in biological knowledge and fisheries monitoring. Accurate taxonomic resolution, combined with species-level landing data, targeted biological studies, and periodic stock assessments, is essential for effective fisheries management and conservation planning. Overall, the study highlights the importance of integrating taxonomic, biogeographic, and fisheries perspectives to support sustainable utilisation and long-term conservation of sciaenid resources in Indian waters.

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Author contributions

Conceptualisation: SAT, RJN; Methodology: SAT; Data Collection: SAT, VKM; Data Analysis: SAT Writing Original Draft: SAT; Writing Review and Editing: SAT, RJN; Supervision: RJN

Data availability

Data will be made available on request

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of samples/ protected environments

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Spatiotemporal variation in intertidal isopod diversity along the southern Kerala coast: Indicators of coastal ecosystem health under environmental changes

Arya Unni*, R. S. Balamurali, A. S. Shibina and S. S. Amrutha
Mahatma Gandhi College, Thiruvananthapuram- 695 004, Kerala, India.

*Correspondence e-mail: aryaunni.8@gmail.com
ORCiD: https://orcid.org/0009-0009-8924-6149

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Original Article

Abstract

Diverse benthic communities that are essential to coastal resilience are supported by intertidal zones, which are among the most dynamic and climate-sensitive ecosystems. Over the course of two years (2018–2020), this study examines the spatiotemporal diversity and abundance of four intertidal isopod species (*Ligia dentipes, Alloniscus perconvexus, Dynamenella lauticauda*, and *Cirolana bovina*) at three coastal sites on the southern Kerala coast: Kovalam, Thirumullavaram, and Varkala. Tidal gradients (high, mid, and low tide) and seasonal intervals (pre-monsoon, monsoon, and post-monsoon) were sampled using stratified quadrats. Community structure was assessed using diversity indices, such as Shannon-Wiener, Simpson's, Fisher's Alpha, and Berger-Parker Dominance. With low species richness and strong dominance, Varkala demonstrated biotic impoverishment, whereas Kovalam displayed the greatest diversity and ecological stability. Seasonal trends showed that the best conditions for isopod proliferation occurred after the monsoon, perhaps as a result of better moisture regimes and organic detritus input. These patterns show how sensitive isopod assemblages are to changes in the environment, making them useful bioindicators of the health of intertidal ecosystems. With implications for SDG 14 (Life Below Water) and wetland conservation policies, the findings support climate-responsive biodiversity monitoring. The significance of baseline faunal evaluations in predicting and controlling ecological change along India's sensitive coastal habitats is highlighted by this study.

Keywords: *Marine isopods, intertidal diversity, bioindicators, climate variability, Kerala coast, ecosystem health*

Introduction

Coastal ecosystems are among the most dynamic and ecologically significant environments, supporting high biological diversity and complex trophic interactions that contribute to ecosystem stability and productivity (Henseler *et al*., 2019). Intertidal zones, in particular, experience strong environmental gradients such as tidal fluctuations, wave action, and variable moisture conditions, making them highly sensitive to both natural and anthropogenic disturbances (Defeo and McLachlan, 2005). The structure and functioning of these ecosystems are therefore closely linked to the composition and diversity of benthic communities inhabiting them.

Among benthic organisms, free-living marine isopods play an important ecological role in coastal environments. They contribute significantly to organic matter decomposition, nutrient cycling, and energy transfer within food webs, while also serving as prey for higher trophic levels (Poore and Bruce, 2012; Unni *et al.,* 2023). Due to their close association with substrate conditions and environmental parameters, isopods are highly responsive to ecological changes and are widely recognised as effective bioindicators of habitat quality and ecosystem health (Gray, 2002; Warwick and Clarke, 1993). Biodiversity assessment in such systems is commonly carried out using a combination of diversity indices that capture species richness, evenness, and dominance patterns. These metrics provide a comprehensive understanding of community structure and are essential for detecting ecological imbalances and environmental stress (Clarke and Warwick, 2001). Spatial and temporal variations in diversity are particularly important in intertidal ecosystems, where factors such as tidal zonation, seasonal changes, and habitat heterogeneity strongly influence species distribution and abundance.

Despite the ecological importance of intertidal fauna, studies focusing on the spatiotemporal variation of free-living marine isopods along the southwest coast of India, particularly Kerala, remain limited. Most existing studies have addressed general benthic diversity or environmental influences, with relatively little emphasis on isopod community structure across multiple habitats, tidal gradients, and seasonal cycles. This lack of detailed baseline data restricts our ability to understand ecological patterns and assess environmental changes in these vulnerable coastal systems.

In this context, the present study investigates the diversity and abundance of four intertidal isopod species-*Ligia dentipes, Alloniscus perconvexus, Dynamenella lauticauda*, and *Cirolana bovina*-across three coastal sites (Kovalam, Thirumullavaram, and Varkala) along the southern Kerala coast. By integrating spatial (site and tidal depth) and temporal (seasonal) analyses over two years, the study aims to evaluate patterns of community structure and identify environmental factors influencing isopod distribution. The findings of this study are expected to provide baseline ecological data for intertidal isopod assemblages and contribute to biodiversity monitoring and conservation strategies. Furthermore, the use of isopods as bioindicators offers valuable insights into coastal ecosystem health, supporting sustainable management and climate-responsive assessment of marine habitats.

Material and methods

Study sites

The beaches of Kovalam, Varkala, and Thirumullavaram (Kerala, India) were selected based on the presence of rocky and structurally complex intertidal habitats, which provide suitable microhabitats known to support higher diversity and abundance of free-living marine isopods.

Sampling design

At each location, 100-meter transects parallel to the beach were used for stratified random quadrat sampling (25 cm x 25 cm). For two years, sampling took place at three tidal heights (high, mid, and low tide zones) throughout the premonsoon, monsoon, and postmonsoon seasons.

Specimen collection and identification

Isopods were selected by hand, sieved through a 0.5 mm mesh screen, preserved in 70% ethanol, and then identified in a laboratory. Specimens were identified using a comparative taxonomic approach based on published descriptions and regional taxonomic literature. As no single comprehensive key was available, diagnostic characters were cross-verified across multiple sources. Four different intertidal isopod species were identified - *Ligia dentipes, Dynamenella laticauda, Alloniscus perconvexus* and *Cirolana bovina*.

Data analysis

Species richness, evenness, and dominance were quantified by using Fisher's Alpha (Fisher *et al.*, 1943), Shannon–Wiener Index (Shannon, 1948), Simpson's Index (Simpson, 1949), Pielou's Evenness (Pielou, 1966), Berger–Parker Dominance (Berger and Parker, 1970), Margalef Index (Margalef, 1958), and Menhinick Index (Menhinick, 1964). All diversity indices were calculated using PAST 4.03 (Paleontological Statistics Software) (Hammer *et al.*, 2001). Abundance metrics included total count, relative abundance, and density. These indices are central to ecology, conservation biology, sociology, and other disciplines concerned with variation within complex systems (ScienceDirect, n.d. 2025).

Results

Site-wise diversity

The total diversity analysis shows that the three coastal areas differ significantly in species richness, evenness, and dominance.

Kovalam has the highest level of overall diversity among the three beaches. The Fisher's Alpha (0.4594), Margalef (0.3784), and Menhinick (0.07593) indices indicate comparatively higher species richness. The species' even distribution and high diversity are confirmed by both the Shannon-Wiener Index (H′ = 1.373) and Simpson's Index (1–D = 0.7438). The distribution of individuals within the species is about equal, according to Kovalam's Pielou's Evenness (J′ = 0.9906). Furthermore, the Berger-Parker Dominance Index (0.2868) is the lowest of all, indicating that the assemblage is not dominated by a single species. Together, these findings suggest that Kovalam is home to a more diversified and well-balanced isopod community.

The second-most species-diverse area is Thirumullavaram. Its Menhinick Index (0.06047), Margalef Index (0.2561), and Fisher's Alpha (0.3373) all show moderate richness. A community with a respectable degree of heterogeneity is indicated by diversity values like the Simpson's Index (0.6556) and the Shannon-Wiener Index (1.082). Pielou's Evenness (0.985), which remains high, shows that the distribution of species is fairly even. The Berger-Parker Dominance Index

(0.4124) shows moderate dominance, even if it is slightly higher than Kovalam's. This indicates that, while having somewhat less variation than Kovalam, Thirumullavaram maintains a stable and reasonably diverse isopod colony.

Varkala has the lowest species richness and diversity. With Fisher's Alpha (0.2283), Margalef (0.1373), and Menhinick (0.05245) scores in the lowest end, richness appears to be limited. Both the Shannon-Wiener Index (0.6931) and Simpson's Index (0.4999) indicate low diversity and a community that might be dominated by one or two species. Despite this, evenness (J′ = 0.9999) is strong, which could be explained by the small number of uniformly distributed species. The highest of all, the Berger-Parker Index (0.5062), indicates a single species' dominance, which lowers the variety of the community as a whole (Table 1).

Depth-wise diversity

A distinct depth-associated gradient appeared when data were examined by tidal zone for both years: Kovalam consistently displayed high species richness (Taxa_S = 4) at all depths. The mid and low tide zones showed the highest levels of evenness (J′ > 0.97), low dominance (Berger–Parker < 0.36), and diversity (Shannon's H′ > 1.35; Simpson's 1–D > 0.73). These patterns show a stable and rich colony that is supported by lower tidal level environmental circumstances. This pattern was also observed at Thirumullavaram, where diversity increased from high to low tide. In comparison to the high tide zone (H′ = 0.7239), the mid and low tide zones had greater Simpson's (1–D = 0.6418) and Shannon-Wiener values (H′ = 1.063), suggesting favourable conditions for species diversity in submerged areas. At all depths, Varkala's richness was restricted (Taxa_S = 1-2). One species dominated the whole high tide zone (Berger–Parker = 1.0; H′ = 0), while the mid and low zones showed only slight increases in diversity (H′ < 0.7). Here, high evenness ratings are more likely to result from consistently low species populations than from actual ecological balance (Table 2).

Table 1. Overall Diversity Indices for Isopods at the Three Study Sites (Combined Data)

Diversity index	Varkala	Thirumullavaram	Kovalam
Number of Species (S)	2	3	4
Total individuals (N)	1454	2461	2775
Simpson's dominance Index (D)	0.5001	0.3444	0.2562
Simpson's index (1–D)	0.4999	0.6556	0.7438
Shannon–Wiener index (H′)	0.6937	0.9685	1.1674
Pielou's evenness (J′)	1.0000	0.8825	0.8413
Fisher's alpha	0.1134	0.2319	0.3554
Berger–Parker Dominance index	0.8123	0.6729	0.5423
Menhinick's index	0.0525	0.0604	0.0756
Margalef's richness index	0.2747	0.4572	0.6407

Table 2. Depth-wise diversity indices across Kovalam, Thirumullavaram, and Varkala (Combined 2018–2019)

Indices	K1K2H	K1K2L	K1K2M	T1T2H	T1T2L	T1T2M	V1V2H	V1V2L	V1V2M
Berger-Parker	0.4298	0.3604	0.3447	0.5654	0.5107	0.4605	1	0.6637	0.5721
Brillouin	1.232	1.344	1.355	0.7116	1.01	1.056	0	0.6335	0.6773
Chao-1	4	4	4	3	3	3	1	2	2
Dominance_D	0.3115	0.2676	0.2621	0.5019	0.3882	0.3582	1	0.5536	0.5104
Equitability_J	0.9067	0.976	0.9837	0.6589	0.9251	0.9675		0.9212	0.9849
Evenness_e^H/S	0.8786	0.9672	0.9776	0.6875	0.921	0.965	1	0.9469	0.9896
Fisher_alpha	0.636	0.5179	0.5122	0.4439	0.3795	0.3783	0.1442	0.2536	0.2561
Individuals	342	1171	1262	382	1028	1051	148	675	631
Margalef	0.5142	0.4246	0.4201	0.3364	0.2884	0.2875	0	0.1535	0.1551
Menhinick	0.2163	0.1169	0.1126	0.1535	0.09357	0.09254	0.0822	0.07698	0.07962
Shannon_H	1.257	1.353	1.364	0.7239	1.016	1.063	0	0.6385	0.6827
Simpson_1-D	0.6885	0.7324	0.7379	0.4981	0.6118	0.6418	0	0.4464	0.4896
Taxa_S	4	4	4	3	3	3	1	2	2

Seasonal variation

Over two years, the seasonal study showed significant temporal trends: In every season, Kovalam showed the greatest and most consistent diversity. The Shannon-Wiener Index varied from 1.267 (monsoon) to 1.353 (postmonsoon), with the postmonsoon having the lowest dominance (Berger–Parker = 0.3301). Ecological robustness to seasonal fluctuations was demonstrated by the consistently high richness (Fisher's Alpha = 0.5198–0.6339) and even distribution (J′ > 0.96). Throughout the seasons, Thirumullavaram's diversity remained steady, and its richness was moderate. With Shannon H′ ranging from 1.068 to 1.092 and Fisher's Alpha about 0.4074, there was little seasonal variation. The dominance and evenness indices stayed within reasonable boundaries. Varkala, on the other hand, maintained a straightforward composition throughout. In all seasons, species richness did not surpass two species, and diversity indices stayed constant (Shannon

H′ ≈ 0.692; Berger–Parker > 0.52), indicating that seasonal change was restricted by environmental factors (Table 3).

Abundance trends

Kovalam had the highest total abundance (2,775 individuals) throughout all sampling efforts, followed by Thirumullavaram (2,461) and Varkala (1,454). In terms of depth, higher abundance was consistently supported by mid and low tidal zones throughout sites, with Kovalam mid tide producing the highest count (1,262 individuals). Because of the increased moisture, detritus availability, and substrate stability in the mid and lower intertidal zones, this depth-related pattern highlights their ecological favorability. All three sites—Kovalam (1,142), Thirumullavaram (1,124), and Varkala (659)—saw the highest abundance during the postmonsoon season. These patterns imply that isopod growth is encouraged by post-monsoon environmental factors, including stabilised salinity and organic intake (Table 4).

Species-level abundance

Alloniscus perconvexus and *Ligia dentipes* were the two most prevalent and dominant of the four species, especially in mid and low tidal zones. Although it was relatively limited, *Dynamenella lauticauda* made a substantial contribution in Kovalam. The least common species, *Cirolana bovina*, was mostly found at mid-depths beneath damp substrates.

Visual summary

Figures 1–6, represented through bar and radar charts, clearly illustrate the observed trends in species diversity across the study sites. Under all circumstances, Kovalam exhibited a broad

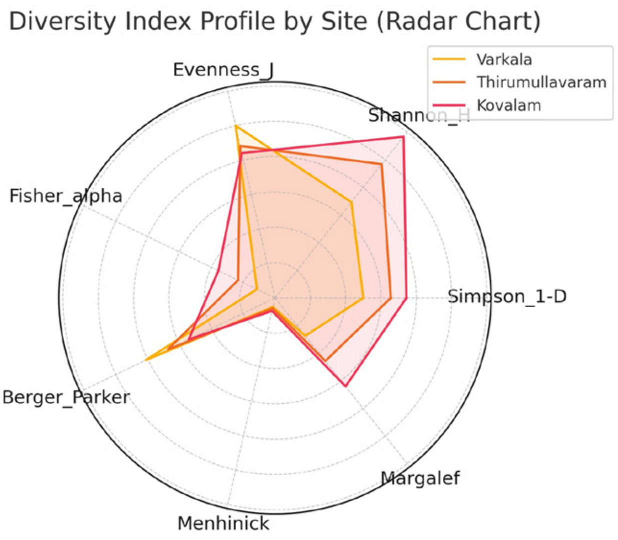

Fig. 1. Radar chart illustrating the multivariate diversity profile of isopod communities at the three study sites. Each axis represents a different diversity index, allowing visual comparison of species richness, evenness, and dominance patterns among Varkala, Thirumullavaram, and Kovalam based on aggregated data of 2018-2019

Table 3. Combined diversity indices of isopods across three coastal sites and three seasons over two years

Parameters	V(PRE)	V(M)	V(POST)	T(PRE)	T(M)	T(POST)	K(PRE)	K(M)	K(POST)
Taxa_S	2	2	2	3	3	3	4	4	4
Individuals	401	394	659	695	642	1124	734	899	1142
Dominance_D	0.5003	0.5016	0.5011	0.3469	0.3374	0.3537	0.2729	0.3177	0.2663
Simpson_1-D	0.4997	0.4984	0.4989	0.6531	0.6626	0.6463	0.7271	0.6823	0.7337
Shannon_H	0.6929	0.6916	0.692	1.077	1.092	1.068	1.337	1.267	1.353
Evenness_e^H/S	0.9997	0.9984	0.9989	0.979	0.9938	0.9699	0.9515	0.8878	0.9674
Brillouin	0.6849	0.6834	0.6868	1.068	1.082	1.062	1.323	1.256	1.344
Menhinick	0.09988	0.1008	0.07791	0.1138	0.1184	0.08948	0.1476	0.1334	0.1184
Margalef	0.1668	0.1673	0.1541	0.3056	0.3094	0.2847	0.4546	0.4411	0.4261
Equitability_J	0.9996	0.9977	0.9984	0.9806	0.9944	0.9722	0.9641	0.9141	0.9761
Fisher_alpha	0.2744	0.2752	0.2544	0.4024	0.4074	0.3747	0.5567	0.5391	0.5198
Berger-Parker	0.5112	0.5279	0.5235	0.4014	0.3769	0.4395	0.342	0.4739	0.3301
Chao-1	2	2	2	3	3	3	4	4	4

Table 4. Total Abundance of isopods by Site, Depth Zone, and Season. This table summarises the total number of individuals collected from three coastal sites (Kovalam, Thirumullavaram, and Varkala) over two years (2018–2020), categorised by tidal depth and seasonal period

Site	Total individuals	High tide zone	Mid tide zone	Low tide zone	Premonsoon	Monsoon	Postmonsoon
Kovalam	2775	342	1262	1171	734	899	1142
Thirumullavaram	2461	382	1051	1028	695	1124	1242
Varkala	1454	148	631	675	401	394	659

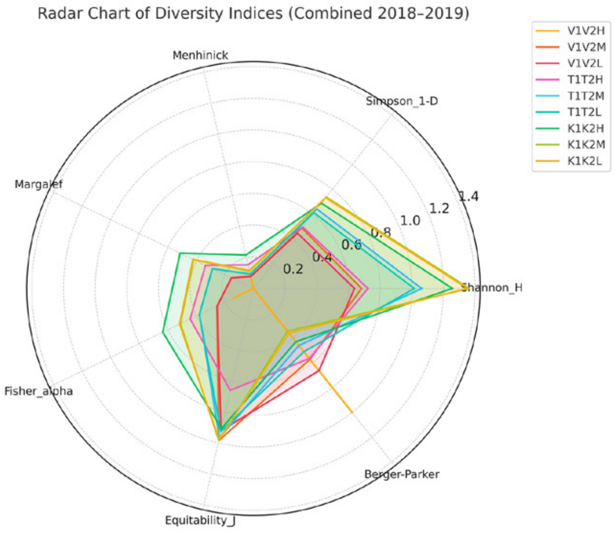

Fig. 2. Radar chart comparing diversity indices across combined site-depth zones (2018–2019) for the three coastal locations. Broader polygons associated with Kovalam low and mid tide zones (K1K2L, K1K2M) indicate consistently higher diversity and evenness. In contrast, the compact shape of Varkala high tide (V1V2H) reflects poor diversity and a dominance by a single species. This composite visualisation underscores depth- and site-related heterogeneity across the study area over two years

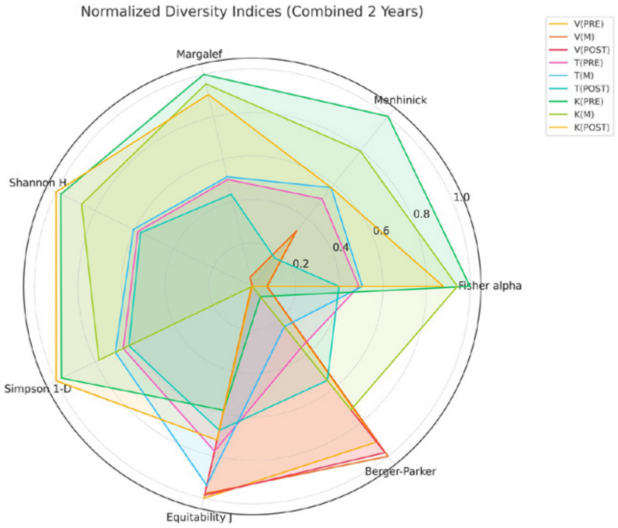

Fig. 3. Radar chart of normalised diversity indices across site-season combinations for the combined two-year dataset. Diversity indices are scaled between 0 and 1 to allow visual comparison of richness, dominance, and evenness patterns across sites and seasons. Each polygon represents one site-season unit (e.g., T(POST)), illustrating multi-dimensional ecological structure. The chart highlights the superior diversity profile of Kovalam and the relatively constrained but stable community structure at Varkala

and well-balanced diversity profile, indicating comparatively greater ecological stability and evenness. Thirumullavaram showed a steady but moderate diversity pattern, suggesting relatively consistent but less pronounced species variation. In contrast, Varkala appeared to be environmentally constrained, as reflected by its high species dominance and comparatively low species richness.

Discussion

Site-wise diversity

There were notable differences in diversity patterns among the three research locations. With the lowest Berger-Parker dominance (0.5423) and strong values in Fisher's Alpha (0.3554), Shannon-Wiener Index (H′ = 1.1674), and Simpson's 1-D (0.7438), Kovalam consistently showed the largest species diversity. Due to good sediment structure, complex habitats, and little human interference, this represents a rich, uniform, and ecologically stable isopod community (Gray, 2002; Poore and Bruce, 2012). Kovalam's ecological appropriateness is further supported by its overall abundance of 2,775 individuals. With three species, intermediate diversity values, and high evenness (J′ = 0.8825), Thirumullavaram had moderate variety. Its community displayed moderate dominance (Berger-Parker = 0.6729) and a significant total abundance (2,461 individuals), suggesting rather stable and resource-rich environments. With only two species and strong dominance, Varkala, on the other hand, had the lowest diversity and richness (Berger-Parker = 0.8123). Although evenness seemed excellent (J′ = 1.0000), this is a statistical consequence of its low species count. Varkala's low diversity and abundance—just 1,454 individuals—indicate ecological filtration or environmental stresses. These patterns are consistent with known relationships between environmental stability, habitat complexity, and diversity (Pearson and Rosenberg, 1978; Warwick and Clarke, 1993).

Depth-wise diversity

Community structure was significantly impacted by intertidal depth gradients. The mid and low tide zones at Kovalam had the largest diversity, with Simpson's 1-D values above 0.68 and Shannon's H′ exceeding 1.2. Additionally, compared to the high tide zone (342), these regions maintained reduced dominance and higher species richness (Fisher's Alpha up to 0.584), which correlated with higher isopod abundance (1,262 and 1,171 individuals, respectively). Similar trends were seen in Thirumullavaram, where variety and abundance were higher at low (1,028) and mid (1,051) tide levels than at high tide (382). Although diversity increased somewhat with depth, Varkala's upper zones were species-poor and dominated by a single taxon (H′ = 0; 1–D = 0). These results align with worldwide observations of vertical zonation caused by desiccation, wave exposure, and substrate moisture (Defeo and McLachlan, 2005; Duggins *et al.*, 1989).

Seasonal diversity

With Fisher's Alpha ranging from 0.5567 to 0.6339 and peak Shannon's H′ values in the postmonsoon (1.364), the seasonal study showed that Kovalam maintained the highest and most consistent diversity across seasons. A consistently balanced society was indicated by low dominance (Berger-Parker = 0.3247–0.3545) and high evenness (J′ > 0.96). The highest abundance (1,142 individuals) was likewise supported by the postmonsoon, indicating beneficial environmental circumstances following monsoonal disruptions. With reasonably consistent diversity indices (H′ = 1.07–1.09) and a peak in abundance (1,124 individuals) during the postmonsoon, Thirumullavaram showed moderate seasonal change. Wave-induced habitat alterations or species turnover may be the cause of a minor postmonsoon fall in richness. With only two species identified and a low Fisher's Alpha (<0.31), Varkala continued to be species-poor throughout the seasons. Low diversity was concealed by high evenness values, but its damaged ecological status is reflected in low seasonal abundance (401–659 individuals) and high dominance (Berger-Parker > 0.5). These findings align with the impact of seasonal environmental factors on intertidal communities, including salinity, rainfall, and organic input (Attrill and Rundle, 2002).

Integrated spatial-temporal insights

Radar and bar chart profiles revealed that the most varied and well-balanced isopod communities were located in Kovalam's mid and low tide zones throughout postmonsoon and premonsoon periods. Varkala's high tide zones, on the other hand, were always dominated and species-poor throughout the year. In line with other research that links diversity to habitat stability and less human disturbance, these patterns were reflected in abundance data, confirming that Kovalam maintains more ecological resilience (Bilyard, 1987).

Ecological implications

Kovalam is a priority for conservation because of its high diversity and low dominance, which show strong ecosystem functioning, including trophic complexity and niche complementarity. On the other hand, Varkala's streamlined and dominance-skewed community likely reflects environmental degradation, sediment instability, or anthropogenic influences. Here, lower isopod abundance indicates both decreased population density and decreased variety. These results support the usefulness of isopods as reliable bioindicators of the health of intertidal ecosystems (Salas *et al.*, 2006; Warwick and Clarke, 1993).

Climate change implications and socio-ecological relevance

Intertidal ecosystems, including the habitats examined in this study, are seriously threatened by climate change. By changing moisture regimes, organic input, and sediment stability, variations in temperature, precipitation, and sea level rise can have a direct impact on intertidal isopod populations (Defeo and McLachlan, 2005; Attrill and Rundle, 2002). For example, if sea levels rise, there may be less habitat available in high and mid-tide zones, which could increase competition and perhaps result in the extinction of local species (Duggins *et al.*, 1989). Furthermore, the seasonal availability of organic matter and detritus that supports isopod populations may be disrupted by changes in monsoon patterns, as predicted under climate change scenarios (Unni *et al.*, 2023).

Intertidal isopods are essential to the health of nearshore ecosystems that sustain artisanal fisheries and wetland livelihoods because of their function in nutrient cycling and detritus decomposition (Salas *et al.*, 2006). Fish nursery environments, organic matter recycling, and coastal food webs may all be impacted by changes in isopod diversity (Warwick and Clarke, 1993). As a result, keeping an eye on isopod assemblages offers an affordable bioindicator method for evaluating the health of ecosystems under shifting climate regimes (Gray, 2002). This study emphasises the necessity of combining isopod diversity monitoring with sustainable fishing methods, coastal management, and climate adaptation techniques. The results highlight the significance of biodiversity assessments in fostering resilience and sustainable livelihoods for coastal communities by being in line with the Sustainable Development Goals (SDG 14–Life Below Water) (Henseler *et al.*, 2019; Protasov *et al.*, 2019).

Conclusion

The study concludes that free-living isopod diversity and abundance along the southern Kerala coast vary distinctly across sites, depths and seasons. Kovalam supported the most diverse and ecologically balanced isopod community, indicating relatively stable habitat conditions, whereas Thirumullavaram showed moderate but consistent diversity. In contrast, the high dominance and low species richness observed at Varkala suggest a simplified community structure, possibly reflecting habitat degradation and ecological stress. Overall, the use of multiple diversity indices provided a comprehensive assessment of intertidal biodiversity and ecological integrity, highlighting the potential of free-living isopods as sensitive bioindicators for monitoring coastal ecosystem health.

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Author contributions

Conceptualisation: AU; Methodology: AU; Data Collection: AU, ASS; Data Analysis: AU, SAS; Writing Original Draft: AU; Writing Review and Editing: BRS; Supervision: BRS.

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of samples/ protected environments.

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New distribution records of three species of soft corals (Octocorallia: Malacalcyonacea) from the central Indian Ocean islands

Nayana Narayanankutty[1], C. A. Riyas[1, 2], Minu Thomas[1], K. K. Idreesbabu[2] and S. Sureshkumar[1*]

[1]Kerala University of Fisheries and Ocean Studies, Panangad-682 506, Kerala, India.
[2]Department of Science and Technology, Kavaratti-682 555, UT of Lakshadweep, India.

*Correspondence e-mail: suresh@kufos.ac.in
ORCiD: https://orcid.org/0000-0001-5609-4024

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Original Article

Abstract

Lakshadweep forms the northernmost extension of the Central Indian Ocean Islands Ecoregion. Although 37 species of soft corals have been reported previously, their taxonomic identity and genetic diversity remain poorly resolved. In this study, we applied an integrated taxonomic approach combining external morphology, sclerite characteristics, and partial mitochondrial *mtMutS* gene sequences to identify soft corals from Lakshadweep. Three species, *Lobophytum catalai*, *Sclerophytum polydactylum*, and *Dendronephthya hemprichi,* were confirmed from the Lakshadweep Archipelago. These findings provide updated records for the region and contribute to a better understanding of the soft coral diversity in the Lakshadweep Archipelago. The results form a useful baseline for future research and conservation of octocorals in Indian coral reef ecosystems.

Keywords: *Integrated taxonomy, mitochondrial DNA, mtMutS, Lakshadweep Archipelago*

Introduction

The soft corals of the Order Malacalcyonacea (Class Octocorallia), commonly known as octocorals, are sedentary, colonial marine animals distributed mostly in the Indo-Pacific region (Bayer, 1973; Fabricius and Alderslade, 2001). They are an important component of the coral reef ecosystem as they contribute significantly to biomass and provide microhabitats for associated organisms (Bayer, 1961; Buhl-Mortensen and Mortensen, 2005; Haverkort-Yeh *et al*., 2013; Shahbazi *et al*., 2021). Compared to their reef-building Scleractinian coral counterparts, there is a knowledge gap about the relationships between octocorals and their associated fauna (Stella *et al*., 2011; Calcinai *et al.,* 2013; Gaikwad *et al.,* 2021).

The Lakshadweep archipelago is a group of oceanic coral islands that lie between latitudes 8°-14°N and longitudes 71°-74°E, situated on the northern part of the Laccadive-Chagos ridge in the central Indian Ocean (Mallik, 2017). Generally, information on octocorals from the central Indian Ocean islands, such as the Maldives and Lakshadweep, is very limited. The first comprehensive survey of this region was conducted by Gardiner (1903), who documented the fauna and geography of the Maldives and Laccadive Archipelago during the 1899–1900 expedition. Apart from the 'Investigator Expedition' collections (T and Henderson, 1906 and Thomson and Simpson, 1909), the taxonomic reports on Maldives and Lakshadweep soft corals are found in the publications of Pratt (1903, 1905), Hickson (1903, 1905), van Ofwegen and Vennam (1991), Alderslade and Shirwaiker (1991), Vennam and van Ofwegen (1996), Mary and Sluka (2014), and Narayanankutty *et al.* (2025).

Soft corals have received comparatively less research attention than reef-building scleractinian corals. The first record of the Lakshadweep soft corals goes back to van Ofwegen and Vennam (1991), who reported 19 species from the islands of Kavaratti, Agatti, and Bangaram. Then, Aderslade and Shirwaiker (1991) reported 17 species from the Kavaratti atoll. Vennam and van Ofwegen (1996) reported 11 species from different islands. These works come from the expeditions conducted in 1985, 1987-1989, and 1992 by the National Institute of Oceanography, India. The purpose of this collection was to study the bioactive compounds of soft corals. Then, 44 species of soft corals were identified from the Minicoy islands by Mary and Sluka (2014), and they were not confirmed at the species level. A recent study by Narayanankutty *et al.* (2025) identified 15 soft coral species: 12 at the genus level and 3 at the species level.

For octocoral molecular analysis, the mtMuts gene evolves more rapidly than COI, making it a more suitable barcoding marker for octocoral identification (McFadden *et al.,* 2011; McFadden *et al.,* 2014; Benayahu *et al.,* 2018). Molecular analysis can resolve the identity of cryptic species, is a useful tool for characterising morphological variants of species, and rapidly assesses and compares the biodiversity of octocorals (McFadden *et al.,* 2017; Benayahu *et al.,* 2018; Quattrini *et al.,* 2019; Shahbazi *et al.,* 2021).

In this study, we employ an integrative taxonomic approach combining morphology and mtMutS sequence data to assess soft coral diversity in Lakshadweep. We report three new distributional records and provide updated molecular confirmation of regional octocoral diversity. This study establishes a baseline framework for future biodiversity assessment and phylogenetic research in the central Indian Ocean.

Material and methods

Sample collection and morphological analysis

The collection was made from 2021 to 2022 from the different islands of Lakshadweep. The specimens were collected using SCUBA diving at depths of 5 to 30 m. Materials were preserved in 75% EtOH, and small tissue pieces were stored in 100% molecular-grade EtOH for DNA extraction. The specimens were deposited in the Biodiversity Lab, Kerala University of Fisheries and Ocean Studies, Kochi, India. The specimens were identified to the genus level following Fabricius and Alderslade (2001), and the sclerites were extracted from the tissue using 10% Sodium hypochlorite.

During the study period, samples were opportunistically collected from certain reef areas in the Lakshadweep Islands. Due to logistical and weather-related factors, the sampling effort was limited to easily accessible locations. Consequently, a subset of the regional soft coral diversity is represented by the geographic coverage and number of specimens.

DNA extraction and amplification

DNA was extracted from ethanol-preserved samples using the Puregene DNA isolation kit (Invitrogen Thermo Fisher Scientific, USA). The mitochondrial mutS homolog (*mtMutS*) region was amplified by PCR, yielding fragments of 700–800 bp. Each reaction (25 μL) contained 12.5 μL master mix, 1 μL each primer, 1 μL $MgCl_2$, 8.5 μL nuclease-free water, and 1 μL template DNA. Amplification used primers ND42625F (5′-TACGTGGYACAATTGCTG-3′) (Lepard, 2003) and Mut-3458R (5′-TSGAGCAAAAGCCACTCC-3′) (Sánchez *et al.*, 2003b). PCR conditions were: 94 °C for 3 min, followed by 35 cycles of 94 °C for 30 s, 58 °C for 90 s, 72 °C for 1 min, and a final extension at 72 °C for 5 min. PCR products were purified using the Nucleopore Sure Extract Kit (Genetix, India). The PCR product was sequenced using the Sanger method at AgriGenome Pvt. Ltd (Kochi, India). Four sequences were generated as part of the study.

Sequencing was performed using BigDye Terminator v3.1 (Applied Biosystems) following the manufacturer's protocol, and chromatograms were analysed with Sequencing Analysis Software v5.2. The sequences were compared in NCBI-BLAST for identification. Sinularia mtMutS sequences and outgroup taxa from Sarcophytonidae were retrieved from GenBank. Alignment was performed using BioEdit v7.1.3.0 (Hall, 1999).

Phylogenetic analyses

Four new *mtMutS* sequences were generated and added to a dataset, including two as outgroups, and were aligned using BioEdit 7.1.3.0 (Hall, 1999) and trimmed to 735 bp. The pairwise genetic distance was calculated using MEGA X (Kumar *et al.,* 2018) using the K2P (Kimura 2-parameter) model (Table 1). The maximum likelihood (ML) analysis was performed in IQ-TREE 2.2.0 (Ly-Trong *et al.,* 2022) with the best partition scheme and ultrafast bootstrap support for 1000 iterations. The resultant tree was visualised in iTOL (https://itol.embl.de) (Letunic and Bork, 2021). The generated sequences were deposited in GenBank under accession numbers PV695213-PV695216 (Table 2).

The current analysis did not include nuclear 28S rDNA markers and mitochondrial cytochrome oxidase I (COI). COI is less useful for differentiating closely related taxa in octocorals due to its comparatively modest substitution rates and low species-level resolving power (France and Hoover, 2002; McFadden *et al.*, 2010). Additionally, the limited availability of

Table 1. The interspecific distance between the clades represents families

	Clade 1	Clade 2	Clade 3
Clade 1			
Clade 2	7.7		
Clade 3	9.2	9.9	
Clade 4	10.7	11.2	8.3

Table 2. Voucher information and GenBank accession numbers of mtMutS sequences generated in the present study from Lakshadweep

Species	Voucher No.	Locality	Gene	GenBank Accession No.
Dendronephthya hemprichi	BDLKUFOS-03-002	Kavaratti	*mtMutS*	PV695213
Lobophytum catalai	BDLKUFOS-04-001	Kavaratti	*mtMutS*	PV695214
Sclerophytum polydactylum	BDLKUFOS-04-002A	Agatti	*mtMutS*	PV695215
	BDLKUFOS-04-002B	Kavaratti	*mtMutS*	PV695216

28S rDNA sequences for nephtheid taxa in public databases restricts their comparative utility. Because of its somewhat better phylogenetic resolution in octocorals, *mtMutS* was chosen as the main molecular marker (McFadden *et al*., 2006, 2010).

Results

A consolidated checklist of soft corals from Lakshadweep is provided (Table 3), including 37 previously reported species and the three new records documented in this study. This research increases the known soft coral diversity of the archipelago to 40 species.

Morphological identification

Lobophytum catalai Tixier-Durivault, 1957 (Figs. 1a-b):

Systematics
Phylum – Cnidaria Verrill, 1865
Subphylum – Anthozoa Ehrenberg, 1834
Class – Octocorallia Haeckel, 1866
Order – Malacalcyonacea McFadden, van Ofwegen & Quattrini, 2022
Family – Sarcophytidae Gray, 1869
Genus – Lobophytum Marenzeller, 1886

Type Locality: Fiji Islands
Original name: *Lobophytum catalai* Tixier-Durivault, 1957
Synonyms: *Lobophytum nodosum* Tixier-Durivault, 1969

Taxonomic Reference: Tixier-Durivault, A. (1957). The Alcyonaires of the Museum: I. Family Alcyoniidae. IV. Genus *Lobophytum* (Fin). Bulletin of the National Museum of Natural History, Paris, Ser. 2. 29 (1): 106-111.

Material examined: BDLKUFOS-04-001 (Fig. 1a, b), a piece of a colony collected from the Lagoon area, Kavaratti, Lakshadweep Islands, India. 5 m. Nayana Narayanankutty. 27 February 2022.

Fig. 1. *Lobophytum catalai*. a. *Excitu* photo. b. Sclerites from the areas ; A. Lobes, B. Basilaires

Table 3. Checklist of soft coral species reported from the Lakshadweep archipelago based on previous literature (n = 37) and the present study (n = 3 new records)

No.	Species	Locality	Reference
	Phylum- Cnidaria		
	Subphylum- Anthozoa		
	Class-Octocorallia		
	Order-Malacalcyonacea		
	Family- Cladiellidae McFadden, van Ofwegen and Quattrini, 2022		
	Genus-Cladiella Gray, 1869		
1	*Cladiella krempfi* (Hickson, 1919)	Agatti, Kavaratti, Androth	van Ofwegen and Vennam 1991; Alderslade and Shirwaike 1991; Narayanankutty *et al.,* 2025
2	*Cladiella pachyclados* (Klunzinger, 1877)	Agatti, Androth, Bangaram, Kalpeni, Kavaratti	Vennam and van Ofwegan, 1996
	Genus- Klyxum Alderslade, 2000		
3	*Klyxum flaccidum* (Tixier-Durivault, 1966)	Kavaratti	van Ofwegen and Vennam, 1991

No.	Species	Locality	Reference
	Family–Nephtheidae Gray, 1862		
	Genus–Dendronephthya Kükenthal, 1905		
4	*Dendronephthya hemprichi* (Klunzinger, 1877)	Kavaratti	Present study
	Family- Sarcophytidae Gray, 1869		
	Genus- Lobophytum Marenzeller, 1886		
5	*Lobophytum altum* Tixier-Durivault, 1956	Bangaram	van Ofwegen and Vennam, 1991
6	*Lobophytum batarum* Moser, 1919	Kavaratti	Alderslade and Shirwaike, 1991
7	*Lobophytum catalai* Tixier-Durivault, 1957	Kavaratti	Present study
8	*Lobophytum crassum* von Marenzeller, 1886	Kavaratti	van Ofwegen and Vennam, 1991; Vennam and van Ofwegen, 1996
9	*Lobophytum durum* Tixier-Durivault, 1956	Kavaratti	Alderslade and Shirwaike, 1991
10	*Lobophytum pauciflorum* (Ehrenberg, 1834)	Agatti, Androth, Bangara, Kavaratti	van Ofwegen and Vennam, 1991; Vennam and van Ofwegen, 1996; Narayanankutty *et al.,* 2025
11	*Lobophytum schoedei* Moser, 1919	Bangaram	van Ofwegen and Vennam, 1991
12	*Lobophytum strictum* Tixier-Durivault, 1957	Kavaratti	Alderslade and Shirwaike, 1991
13	*Lobophytum tecticum* Alderslade and Shirwaiker, 1991	Kavaratti	Alderslade and Shirwaike, 1991
	Genus- Sarcophyton Lesson, 1834		
14	*Sarcophyton crassocaule* Moser, 1919	Agatti	van Ofwegen and Vennam, 1991
15	*Sarcophyton glaucum* (Quoy and Gaimard, 1833)	Kavaratti	Alderslade and Shirwaike, 1991
16	*Sarcophyton serenei* Tixier-Durivault, 1958	Kavaratti	Alderslade and Shirwaike, 1991
17	*Sarcophyton spinospiculatum* Alderslade and Shirwaiker, 1991	Kavaratti	Alderslade and Shirwaike, 1991, Vennam and van Ofwegen, 1996
18	*Sarcophyton trocheliophorum* von Marenzeller, 1886	Agatti, Bangaram, Kavaratti	Alderslade and Shirwaike, 1991, Vennam and van Ofwegen, 1996
	Genus- Sclerophytum Pratt, 1903		
19	*Sclerophytum abhishiktae* (van Ofwegen and Vennam, 1991)	Agatti	van Ofwegen and Vennam, 1991
20	*Sclerophytum abruptum* (Tixier-Durivault, 1970)	Agatti, Androth, Kavaratti	Alderslade and Shirwaike, 1991; Vennam and van Ofwegen, 1996
21	*Sclerophytum densum* (Whitelegge, 1897)	Kavaratti	van Ofwegen and Vennam, 1991
22	*Sclerophytum dissectum* (Tixier-Durivault, 1945)	Kavaratti	Vennam and van Ofwegen, 1996
23	*Sclerophytum elongatum* (Tixier-Durivault, 1970)	Kavaratti	van Ofwegen and Vennam, 1991
24	*Sclerophytum facile* (Tixier-Durivault, 1970)	Agatti	van Ofwegen and Vennam, 1991
25	*Sclerophytum gaveshaniae* (Alderslade and Shirwaiker, 1991)	Kavaratti	Alderslade and Shirwaike, 1991
26	*Sclerophytum gaweli* (Verseveldt, 1978)	Bangaram	van Ofwegen and Vennam, 1991
27	*Sclerophytum gravis* (Tixier-Durivault, 1970)	Kavaratti	Vennam and van Ofwegen, 1996
28	*Sclerophytum gyrosum (Klunzinger, 1877)*	Kavaratti	Alderslade and Shirwaike, 1991
29	*Sclerophytum hirtum* Pratt, 1903	Agatti, Kavaratti	Alderslade and Shirwaike, 1991; van Ofwegen and Vennam, 1991; Vennam and van Ofwegen, 1996
30	*Sclerophytum inelegans* (Tixier-Durivault, 1970)	Agatti	van Ofwegen and Vennam, 1991
31	*Sclerophytum jasminae* (Alderslade and Shirwaiker, 1991)	Kavaratti	Alderslade and Shirwaike, 1991
32	*Sclerophytum kavarattiense* (Alderslade and Shirwaiker, 1991)	Kavaratti	Alderslade and Shirwaike, 1991
33	*Sclerophytum leptoclados* (Ehrenberg, 1834)	Kavaratti	Vennam and van Ofwegen, 1996
34	*Sclerophytum lochmodes* (Kolonko, 1926)	Bangaram	van Ofwegen and Vennam, 1991
35	*Sclerophytum murale* (May, 1899)	Agatti, Kavaratti	Alderslade and Shirwaike, 1991; van Ofwegen and Vennam, 1991; Vennam and van Ofwegen, 1996
36	*Sclerophytum numerosum* (Tixier-Durivault, 1970)	Bangaram	van Ofwegen and Vennam, 1991
37	*Sclerophytum parulekari* (Alderslade and Shirwaiker, 1991)	Kavaratti	Alderslade and Shirwaike, 1991
38	*Sclerophytum polydactylum* (Ehrenberg, 1834)	Kavaratti, Agatti	Present study
39	*Sclerophytum querciforme* Pratt, 1903	Kavaratti	Alderslade and Shirwaike, 1991; Narayanankutty *et al.,* 2025
40	*Sclerophytum variabile* (Tixier-Durivault, 1945)	Agatti	van Ofwegen and Vennam, 1991

Diagnosis: Colony encrusting to low mound-like with distinct digitate lobes; lobes rounded distally and laterally compressed. Surface polyps dimorphic: autozooids elevated, arranged irregularly on lobe surfaces; siphonozooids minute, scattered between autozooids (5–8 siphonozooids between adjacent autozooids). Sclerites are predominantly barrel-shaped and spindles; lobes contain elongated spindles with simple or slightly branched tubercles; the surface layer of the stalk bears small rods and clubs. Distinguished from *L. pauciflorum* by the denser arrangement of siphonozooids and the presence of smaller surface clubs.

Description

Colony form: The colony forms a thick, encrusting base with an expanded, disc-like capitulum bearing short, finger-like lobes. Lobes are broad, rounded at the apices, and slightly flattened laterally. The surface is even to slightly wrinkled when preserved.

Polyps: Polyps dimorphic. Autozooids are conspicuous and retractile, each with eight tentacles arranged irregularly on the lobe surface. Siphonozooids are minute, numerous, and scattered between the autozooids, numbering approximately 5–8 between two autozooids.

Sclerites: Sclerites are abundant throughout all tissues. Surface layer of lobes: densely packed spindles, 0.10–0.20 mm in length, with simple to complex tubercles. Interior of lobes: longer spindles, up to 0.30 mm, slightly curved, with prominent tubercles. Surface layer of stalk: small rods and clubs, 0.05–0.10 mm in length, mostly with warted heads. Interior of stalk: irregular spindles, some branched, up to 0.25 mm long. Barrel-shaped sclerites are common throughout the colony and form a diagnostic character.

Colour: In life, colonies are reported as beige to light brown; preserved material appears greyish beige.

Habitat: Occurs in shallow lagoonal habitats and reef flats, attached to hard substrates or coral rubble at depths of 3–10 m.

Remarks: *L. catalai* is morphologically similar to *L. pauciflorum* but differs in hosting a greater number of siphonozooids between autozooids and having smaller surface clubs. Essentially, the main difference lies in the arrangement and density of polyps and the variation in lobe spindles. The Lakshadweep specimen closely matches the diagnostic features described for *L. catalai.*

Distribution: Widespread in the Indo-Pacific: Guam, American Samoa, Micronesia, Vanuatu, New Caledonia, Marshall Islands, French Polynesia, Cook Islands, and Fiji. Reported in India from the Andaman and Nicobar Islands (Jayasree *et al.*, 1996; Rao and Devi, 2003). The present record extends the distribution to the Lakshadweep Archipelago, Arabian Sea, India.

Sclerophytum polydactylum (Ehrenberg, 1834) (Figs. 2a–b)

Systematics
Phylum – Cnidaria Verrill, 1865
Subphylum – Anthozoa Ehrenberg, 1834
Class – Octocorallia Haeckel, 1866
Order – Malacalcyonacea McFadden, van Ofwegen & Quattrini, 2022
Family – Sarcophytidae Gray, 1869
Genus–Sclerophytum Pratt, 1903
Type locality: Red Sea
Original name: *Lobularia polydactyla* Ehrenberg, 1834
Synonyms: *Alcyonium polydactylum* (Ehrenberg, 1834); *Amocella polydactyla* (Ehrenberg, 1834); *Lobularia polydactyla* Ehrenberg, 1834; *Sinularia polydactyla* (Ehrenberg, 1834); *Sinularia compressa* Tixier-Durivault, 1945; *Sinularia candidula* Verseveldt and Benayahu, 1983.

Taxonomic reference: Ehrenberg, C. G. (1834). *Beiträge zur physiologischen Kenntniss der Corallenthiere im Allgemeinen, und besonders des Rothen Meeres, nebst einem Versuch zur physiologischen Systematik derselben.* Abhandlungen der Königlichen Akademie der Wissenschaften zu Berlin, 225–380.

Material examined: BDLKUFOS-04-002A. Inner reef slope, Agatti Island, Lakshadweep, India (10°52′N, 72°11′E), at 10 m depth. Collected by Abdul Riyas, 25 March 2021. BDLKUFOS-04-002B (Figs. 2a–b): Lagoon area, Kavaratti Island, Lakshadweep, India (10°33′N, 72°38′E), at 5 m depth. Collected by Nayana Narayanankutty, 27 February 2022.

Diagnosis: Colony with distinct, firm stalk and numerous digitate lobes of varying sizes, crowded at the capitulum. Polyps monomorphic; siphonozooids absent. Autozooids are small, with openings visible as minute pits on the lobe surface. Sclerites are predominantly clubs and spindles, showing considerable variation in form and size. Surface layer of lobes contains small to long clubs with wide, ornamented heads; surface layer of stalk with broader clubs and irregularly shaped rods. Interior tissues contain thick, elongated spindles and irregular sclerites.

Distinctive features setting *S. polydactylum* apart from related taxa include the combination of crowded lobes, absence of siphonozooids, and the presence of clubs with wide heads and irregular stalked sclerites.

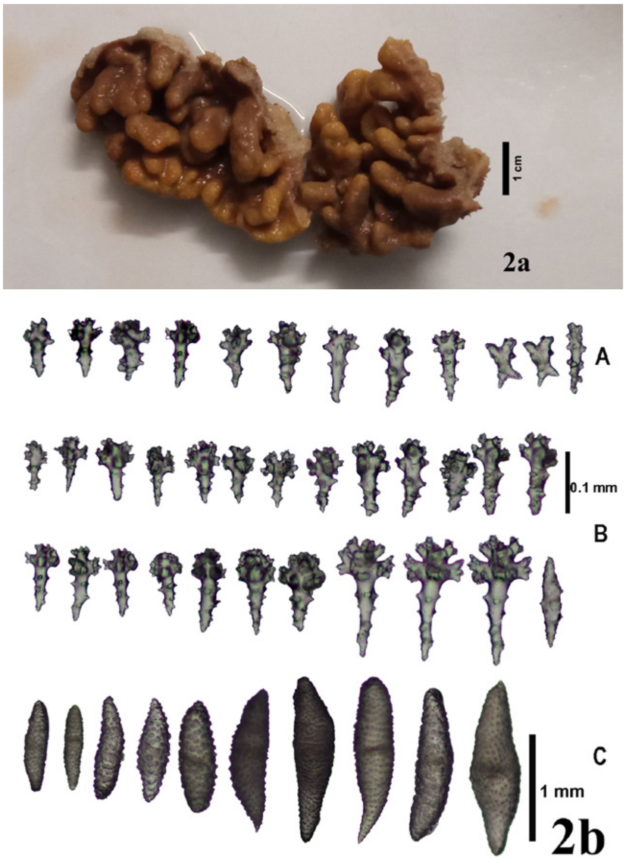

Fig. 2. *Sclerophytum polydactylum*. a. *Excitu* photo. b. Sclerites from the areas – A. Clubs and Spindles of the surface layer, top of colony. B. Clubc and Spindles of the surface layer base of the colony. C. Spindles of the interior of the top and base of the colony

Description

Colony form: Colony erect, lobate, with a well-defined stalk supporting a capitulum bearing crowded, digitiform lobes. Lobes vary in size and may be fused at the base. The surface is smooth, with visible polyp apertures as small pits.

Polyps: Polyps are monomorphic; autozooids are small and evenly spread across lobe surfaces. Siphonozooids are absent, a key diagnostic feature of the species.

Sclerites: Surface layer of lobes: small to long clubs (0.05–0.20 mm), with broad heads covered by tubercles; stalk clubs generally broader. Interior of lobes: elongated spindles (up to 0.30 mm), often slightly curved, with prominent tubercles. Surface of stalk: wide clubs and irregular rods (0.10–0.25 mm). Interior of stalk: thick, irregular spindles (up to 0.35 mm). Sclerites show moderate variability in form, with both symmetrical and irregular types.

Colour: Yellowish-green in life; greyish-yellow when preserved.

Habitat: Occurs in shallow lagoonal and reef slope environments, attached to hard substrates or coral rubble, at depths of 3–15 m.

Remarks: Historically classified as Sinularia, *Sclerophytum polydactylum* has been reclassified following recent phylogenomic evidence supporting Sclerophytum as a distinct monophyletic lineage within Sarcophytidae (McFadden *et al.*, 2022). The Lakshadweep specimens match the diagnostic features of *S. polydactylum*, notably the absence of siphonozooids, crowded lobes, and broad-headed clubs in the surface layer of the stalk.

Distribution: Widely distributed in the tropical Indo-Pacific, including the Red Sea, Persian Gulf, Maldives, Sri Lanka, India (Gulf of Kutch, Andaman and Nicobar), Oman, Iran, Saudi Arabia, Mozambique, Tanzania, Mauritius, Indonesia, Papua New Guinea, Australia, Guam, Chinese Taipei, New Caledonia, and the western Pacific.

Dendronephthya hemprichi (Klunzinger, 1877) (Figs. 3 a-b)

Systematics
Phylum – Cnidaria Verrill, 1865
Subphylum – Anthozoa Ehrenberg, 1834
Class – Octocorallia Haeckel, 1866
Order – Malacalcyonacea McFadden, van Ofwegen & Quattrini, 2022
Family–Nephtheidae Gray, 1862
Genus–Dendronephthya Kükenthal, 1905
Type locality: Red Sea
Original name: *Spongodes hemprichi* Klunzinger, 1877
Synonym: *Spongodes hemprichi* Klunzinger, 1877
Taxonomic Reference: Klunzinger, C. B. (1877). The coral animals of the Red Sea. 1: The Alcyonarians and Malacoderms. Gutmannsche Buchhandlung. Berlin. pp. 98.

Material examined: BDLKUFOS-03-002 (Figs. 3a–b), a colony fragment collected from the reef slope area, Kavaratti Island, Lakshadweep, India (10°33′N, 72°38′E), at a depth of 15 m, collected by Nayana Narayanankutty and Minu Thomas on 13 February 2022.

Diagnosis: Colony glomerate with a flat encrusting base and erect, tree-like branches. The stem and branches are thick, covered with dense, hemispherical polyps arranged in compact clusters. Polyps monomorphic, not retractile. Polyp stalks present, with rounded heads bearing supporting bundles of sclerites. Supporting bundle broad, rigid, and projects slightly beyond the polyp head. Sclerites are mostly

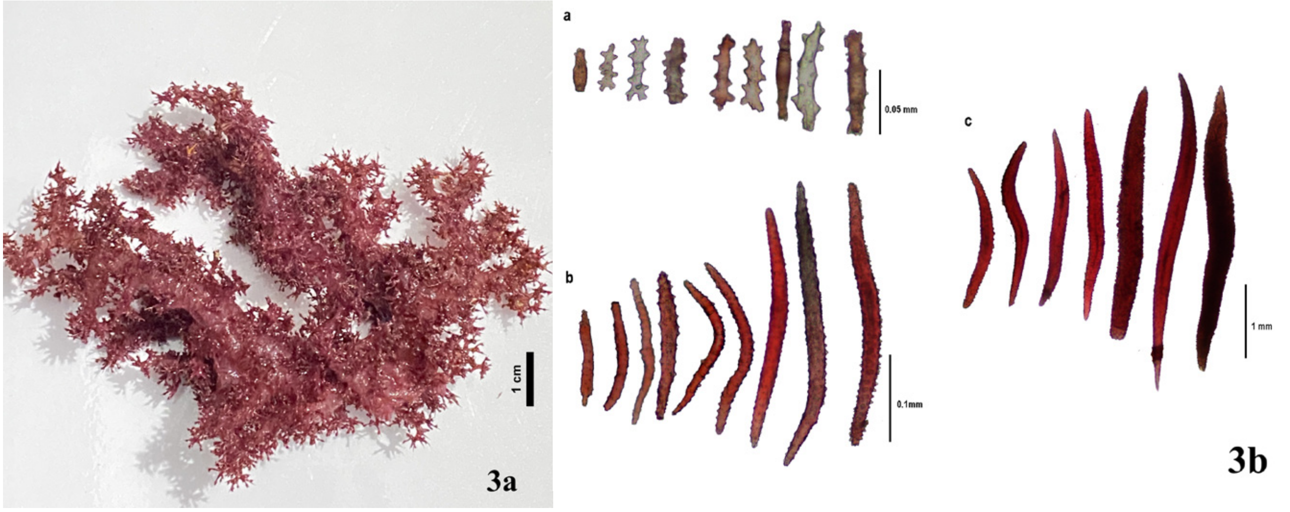

Fig. 3. *Dendronephthya hemprichi* a. *Excitu* photo. b. Sclerites of the A. Irregular shape from stalks, B. Spindles of polyp, C. Spindles of supporting bundle

spindles, bright red in colour, with long, prominent warts; tentacles contain small, flattened, irregularly shaped sclerites forming a mesh-like pattern.

Distinctive features: compact, bushy colony; red-coloured sclerites; polyps in dense, hemispherical clusters; well-developed supporting bundle projecting beyond polyp head.

Description

Colony form: The colony forms a compact, tree-like mass (glomerate) with a broad, flattened base firmly attached to rock or a hard substrate. Branches are short and thick, arising from the main stalk, and densely covered with hemispherical clusters of polyps.

Polyps: Polyps are monomorphic, non-retractile, with a short stalk and a rounded, inflated head. Each polyp bears a prominent supporting bundle of large, warted spindles that extend slightly beyond the head's surface. Tentacles are armed with minute, irregular, flattened sclerites arranged in transverse rows.

Sclerites: Supporting bundle: large spindles, 0.40–0.60 mm long, red in colour, with prominent warted tubercles. Polyp body: small spindles, 0.15–0.30 mm, slender with warted surfaces.Tentacles: minute, flattened and irregularly shaped sclerites forming a reticulate pattern. Stalk: larger, irregular spindles with coarser warts.

Colour: Colony bright wine red in life; sclerites deep red; in preservation, fades to pale reddish-brown.

Habitat: Attached to hard substrates on reef slopes and overhangs at depths of 10–20 m; prefers moderate current conditions typical of lagoonal reef slopes.

Remarks: *Dendronephthya hemprichi* is characterised by compact, bushy colonies with dense, hemispherical polyps and red, spindle-shaped sclerites. The species is one of the more recognisable *Dendronephthya* taxa in the Red Sea region, often distinguished by its bright red pigmentation and well-developed supporting bundles. This report is among the first documented occurrences of *D. hemprichi* from the Lakshadweep Archipelago, extending its known distribution westward within the Indian Ocean.

Distribution: Reported from the Red Sea, Saudi Arabia, Egypt, and the Gulf of Aqaba; also recorded from the western Indian Ocean, including the coasts of Sudan and Eritrea, and now from the Lakshadweep Islands, India.

Molecular identification: For the phylogenetic analysis, we included more species to compare intra- and interspecific variation. Phylogenies were constructed using a total of 25 sequences of the *mtMutS* gene, including the NCBI-retrieved sequences (21) and generated sequences (4). The best substitution model for the gene was HKY+G. In general, nodes that were well supported with bootstrap values (>70) (Fig. 4). The *mtMutS* sequences obtained for the species name have been deposited in GenBank under accession numbers PV695213–PV695216.

Based on the phylogenetic tree, two distinct clades of soft corals were recovered in the analysis. The two clades are divided into four subclades at the genus level. The first clade comprises the genus *Dendronephthya* under the family Nephtheidae, and the second clade comprises the family

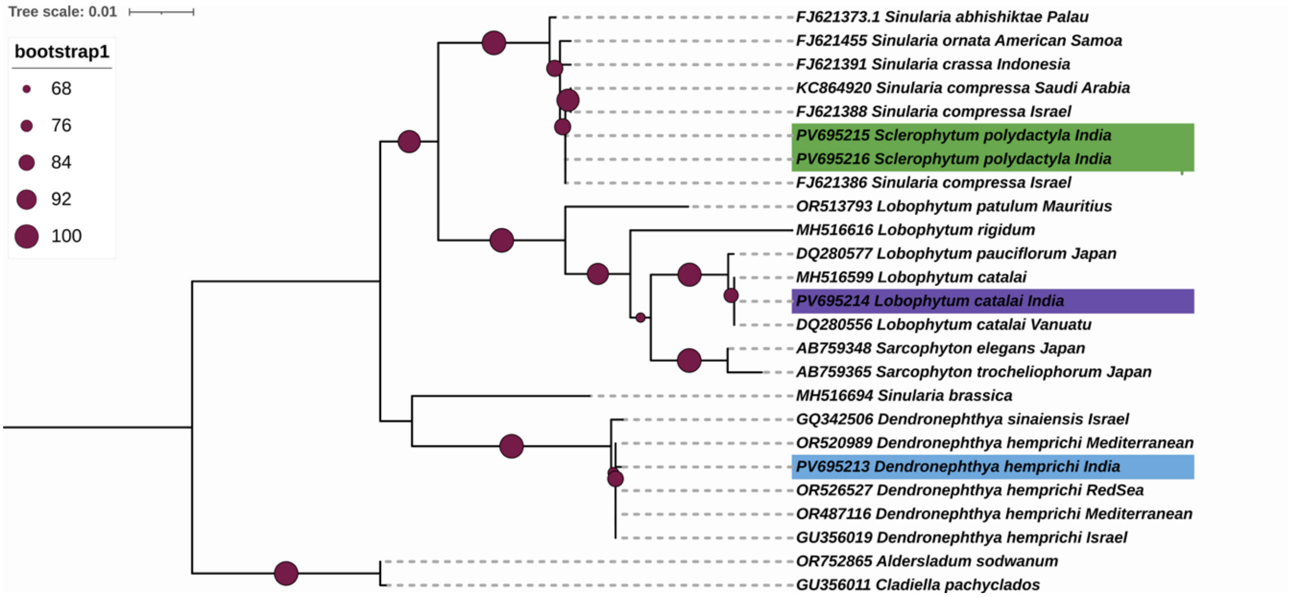

Fig. 4. Maximum likelihood phylogenetic tree of families Sarcophytidae, Sinulariidae, and Nephthidae based on 734 bp of *mtMutS* sequence. Values along the nodes are percentage bootstrap based on 1000 iterations

Sarcophytidae. The Sarcophytidae clade was divided into two subclades; one clade represents the genus *Sclerophytum,* and the other one represents the genera *Lobophytum* and *Sarcophyton*. The clade that formed a monophyletic group of the genus *Sclerophytum* includes the genera *Lobophytum* and *Sarcophyton*.

In the *Dendronephthya* clade, one species of *Dendronephthya hemprichi* was identified from the Lakshadweep, and *D. hemprichi* from the Mediterranean Sea, the Red Sea, and Israel were placed in a single clade. Still, there was a genetic difference of 0 – 0.2% between them. For the species from the Red Sea and Lakshadweep, the genetic difference was zero. Then, the Sclerophytum clade, with two sequences from the Lakshadweep clade, including Sclerophytum polydactylum from Saudi Arabia and Israel, showed genetic differences of 0–0.1%. The Lobophytum species from Lakshadweep is a clade with *Lobophytum catalai* from the South China Sea and Vanuatu, with zero genetic differences. The morphological and genetic analysis of our species confirmed it as *Dendronephthya hemprichi, Sclerophytum polydactylum,* and *Lobophytum catalai.*

The interspecific distance between the four clades mentioned in Table 1: clade 1 was the family Sinulariidae. The genetic distance clearly shows the difference from other clades of the genus, ranging from 7.7 to 10.7%. Clade 2 represents the genus *Dendronephthya* under the family Nephtheidae. This clade also shows a high bootstrap value, and the genetic difference between the genera was 0.1-0.5%. The interspecific genetic distance between the other clades ranged between 7.7 to 11.2%. Clades 3 and 4 represent the family Sarcophytidae, which supports higher bootstrap values. Clade 3 represents the genus *Sclerophytum* with a genetic distance in the genus of 0.1 to 0.7%. The interspecific genetic distance between the clades was 8.3 to 9.9%. Clade 4 comprises the genera Lobophytum and Sarcophyton, with a mean genetic distance between the genera of 0.3-4.1%. The interspecific distance between the clades was 8.3 to 11.2%.

Discussion

Until now, no study has used molecular techniques to identify the soft corals from the Lakshadweep islands. Previous studies in the Lakshadweep archipelago reported 37 species belonging to three families: Cladiellidae, Sarcophytidae, and Nephtheidae (van Ofwegen and Vennam, 1991; Alderslade and Shirwaiker, 1991; Vennam and van Ofwegen, 1996; Mary and Sluka, 2014; Narayanankutty *et al.,* 2025). We emphasise that most previous records of soft corals in the Lakshadweep were based on morphological rather than molecular data. Identification of soft corals was difficult due to their complex structure, cryptic species, and incomplete knowledge of their diversity and distribution (McFadden *et al.,* 2014; Fabricius and Alderslade, 2001). Using the octocoral molecular marker *mtMutS* and the morphological characters, we identified a new record of three species, *Dendronephthya hemprichi, Lobophytum catalai* and *Sclerophytum polydactylum,* from the Lakshadweep Islands. We have not used the other common genetic markers, COI and 28S, because they are unavailable across all species.

A small number of specimens collected from specific reef locations in the Lakshadweep Islands formed the basis for the present investigation. A more comprehensive understanding of species distribution and intraspecific variability could be achieved with increased geographic sampling across more islands and reef ecosystems, even if morphological and genetic data consistently confirm the identification of the taxa under study. The biogeographic and taxonomic interpretations presented here may be enhanced by future research involving larger sample sizes and broader spatial coverage.

The morphological distinctions between the members of the genera Lobophytum and Sarcophyton in the family Sarcophytidae are less obvious, and their relationship may be paraphyletic. The genus *Sclerophytum* is easily distinguished from the Genus *Lobophytum* and *Sarcophyton* by the presence of siphonozooids (McFadden *et al.,* 2006). These three genera are widespread and conspicuous in shallow waters of the Indo-Pacific region. The *Sclerophytum* was the sister group to *Lobophytum* and *Sarcophyton* (McFadden *et al.,* 2006). The species of *Sclerophytum,* the clade formed by monophyletic intra- and interspecific divergence, are not clearly distinguished (Benayahu *et al.,* 2018; Quattrini *et al.,* 2019). Among various species in the genus *Sclerophytum,* there has been a chance of hybridisation; this difference can be due to divergence in isolation (Quattrini *et al.,* 2019). From the different regions of India, 23 species of *Lobophytum* and 44 species of *Sclerophytum* were reported. In the Lakshadweep, a total of nine *Lobophytum* species and 20 *Sclerophytum* species were identified.

The genus *Dendronephthya* is characterised by a wide range of bright colours and is found in the tropical waters of the Indo-Pacific Ocean. They are azooxanthellate (Fabricius *et al.,* 1995) and occur across a wide range of depths (Fabricius and Alderslade, 2001; Grossowicz and Benayahu, 2012). The species classification of the family Nephtheidae is based on morphology (Cordeiro *et al.,* 2022) compared with other soft corals under the family Sarcophytidae. Nowadays, more insights are obtained from phylogenetic analyses of complete mitochondrial genomes (Williamson *et al.,* 2022). The taxonomy of the genus Dendronephthya is quite problematic, and there are no reliable tools for adequately determining species, nor is there any known phylogenetic molecular signal (McFadden *et al.,* 2010). In the Nephthidae species, variation in morphology complicates identification; it may be due to polymorphism within the species (Haverkort-Yeh *et al.,* 2013).

Mary and Sluka (2014) identified seven types of Dendronephthya colonies at the genus level from Minicoy Island, Lakshadweep. A total of 58 species of the Genus *Dendronephthya* were identified across different coral reefs in the Indian region, with most of the records from the Andaman and Nicobar Islands. The fauna of Lakshadweep overlaps with that of the Red Sea and the Western Indian Ocean. Both regions group with the respective species of *Dendronephthya hemprichi* and *Sclerophytum polydactylum,* and the genetic differences range from 0% to 0.1%.

An important contribution to the understanding of the diversity of soft corals and the functioning of reefs in the central Indian Ocean is the documentation of *Lobophytum catalai*, *Sclerophytum polydactylum*, and *Dendronephthya hemprichi* from Lakshadweep. *Lobophytum* and *Sclerophytum* species are recognised as significant space-occupying octocorals that impact the competitive dynamics and benthic community structure on tropical reefs. They frequently interact with scleractinian corals through allelopathic interactions (Coll *et al.*, 1982; Fabricius and Alderslade, 2001). The soft coral Dendronephthya adds to the complexity of the ecosystem and provides structural microhabitats for small invertebrates and reef-associated fauna (Fabricius and Alderslade, 2001). Soft corals influence substratum competition and coral-algal interactions, and certain species are known to generate secondary metabolites that mediate anti-predatory and competitive interactions. Both azooxanthellate and zooxanthellate soft corals engage in plankton capture and nutrient cycling through either photosynthesis (in symbiotic species) or suspension feeding, which enhances reef production. (Coll *et al.*, 1982; Dinesen, 1983; Fabricius and Alderslade, 2001). In terms of biogeography, the presence of these taxa in Lakshadweep broadens their known range in the Indian Ocean and strengthens faunal linkages among the Maldives, the Arabian Sea, and the larger Indo-Pacific reef systems. Their existence highlights the ecological significance of Lakshadweep reefs as part of regional biodiversity and indicates favourable hydrodynamic conditions.

For long-term reef monitoring, baseline biodiversity records are vital, especially in areas susceptible to anthropogenic disturbances, coral bleaching, and climate change. Precise taxonomic documentation enhances the scientific foundation for conservation planning and management strategies across the archipelago and improves species inventories. Soft corals may become increasingly significant in the ecological roles of reefs experiencing shifts in community composition and can greatly contribute to reef structural complexity. Consequently, identifying these species expands Lakshadweep's known biodiversity and offers essential information for future ecological assessments, monitoring efforts, and marine conservation initiatives in the central Indian Ocean.

Conclusions

This study provides the first integrative taxonomic assessment of soft corals from the Lakshadweep Islands using combined morphological and molecular approaches. The documentation of three new distributional records increases the known diversity of the archipelago and establishes a baseline for future biodiversity monitoring and conservation initiatives. Expanded geographic sampling and multilocus molecular analyses are recommended to further resolve octocoral diversity in the central Indian Ocean.

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Author contributions

Conceptualisation: NN, SS; Methodology: NN, CAR; Data Collection: NN, MT, KKI, CAR; Data Analysis: NN, MT; Writing–Original Draft: NN; Writing–Review and Editing: NN, KKI, SS; Supervision – KKI, SS.

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

This study was conducted in accordance with the ethical standards and guidelines established by the Committee for Control and Supervision of Experiments on Animals (CPCSEA), Government of India. All procedures involving animals/humans/the environment, etc., were approved by the appropriate institutional review boards or ethics committees of the Department of Science and Technology, Union Territory of Lakshadweep, Kavaratti, Lakshadweep (LD-0400/1/2/2017- S&TUTLKS), as the case may be.

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Comparative field evaluation of high-saline probiotics on *Artemia franciscana* cyst yield in earthen ponds across seasonal production cycles

M. Samayakannan[1*], N. Vignesh Raja[1], A. Angela Mercy[1], G. Sathya[2], M. Kalaiselvam[2], S. Kandan[1] and A. Abdul Rahman[3]
[1]MPEDA-Rajiv Gandhi Centre for Aquaculture, Sirkazhi-609 109, Tamil Nadu, India.
[2]CAS in Marine Biology, Annamalai University, Parangipettai- 608 502, Tamil Nadu, India.
[3]Adviser /Consultant M/s. Sama Salt Works, Abu Dhabi, UAE.

*Correspondence e-mail: bharathsamay@yahoo.co.in
ORCiD: https://orcid.org/0009-0001-6049-5151

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Original Article

Abstract

Artemia culture systems accumulate organic waste from uneaten feed, moults, and faeces, increasing organic load and ammonia levels, deteriorating water quality. Unlike most aquaculture systems, water exchange is impractical in *Artemia* farming due to the risk of stock escape. Therefore, alternative strategies such as probiotics are used as a sustainable solution for water-quality management. While most commercial probiotics are developed for low-salinity shrimp and fish culture (0–35 ppt), their suitability for hyper-saline *Artemia* systems remains largely untested. This study evaluated two commercial probiotics: Treatment 1 (TR1), Probiotic X (a *Bacillus*-based consortium), and Treatment 2 (TR2), Probiotic Y (*Marinobacter* sp.), over two production cycles-winter (Jan–Apr) and summer (Jun–Oct). Performance was assessed using daily cyst release patterns, reproductive phase duration, total wet cyst yield, and unit area production (kg/ha/crop). Probiotic application significantly prolonged the reproductive phase under hyper-saline conditions. In winter, cyst production in control ponds ceased by 61 days of culture (DOC), whereas probiotic-treated ponds continued until 90 DOC. In summer, control ponds stopped cyst production by 68 DOC, while treated ponds extended cyst release up to 129 DOC. Unit area production followed similar trends; TR1 increased production by 114% (winter) and 304% (summer) over the control, while TR2 achieved increases of 70% and 126%, respectively. Although probiotic Y is more halo-tolerant than probiotic X, probiotic X consistently outperformed probiotic Y and untreated controls, demonstrating that *Bacillus*-based probiotics effectively mitigate water-quality deterioration and enhance cyst production in large-scale, hyper-saline *Artemia* culture systems where water exchange is limited.

Keywords: *Artemia culture, cyst yield, high-saline probiotics, water quality management*

Introduction

Aquaculture, the world's fastest-growing food production sector, continues to expand to meet the rising demand for high-quality protein. However, the industry faces the challenge of sustainable species diversification. While the diversity of aquatic organisms offers vast opportunities for expansion (Duarte *et al*., 2007), persistent constraints such as high larval mortalities limit the realisation of this potential. One of the most critical bottlenecks in larviculture is the consistent supply of high-quality *Artemia* cysts, which are an indispensable live feed during the early life stages of many fish and crustaceans. Consequently, *Artemia* cysts have become a pivotal commodity in the global aquaculture sector. Traditionally, *Artemia* cysts have been harvested from natural hypersaline lakes, such as the Great Salt Lake (USA) and others in Russia, China, and Kazakhstan. However, these natural resources are increasingly threatened by climate change, environmental fluctuations, and over-exploitation, raising concern about long-term supply stability (Wurtsbaugh and Gliwicz, 2001). To reduce dependence on wild harvests, controlled pond-based *Artemia* production systems, especially in solar saltworks, have been developed as an alternative. Since 2007, MPEDA–Rajiv Gandhi Centre for Aquaculture (RGCA) has been demonstrating the feasibility of *Artemia* culture in solar salt pans and trained coastal communities to encourage domestic production and reduce reliance on imports. India, one of the leading countries in shrimp aquaculture, consumes over 300 tonnes of *Artemia* cysts annually, valued at around ₹300 crore (Press Review, 2019), with most imports coming from the USA and China. Shrimp hatcheries typically require 3–5 kg of cysts to produce one million post-larvae, highlighting their economic importance. Regarding the industrial growth, domestic cyst production is still limited despite initiatives by the MPEDA-RGCA. Low and variable yields (about 100 kg/ha/crop) highlight the urgent need to improve cyst productivity per unit area through better pond management.

Successful cyst production depends on optimal water quality and stable pond conditions. A continuous supply of microalgae and supplementary feed is essential to support *Artemia franciscana* growth; however, this daily input steadily increases the accumulation of organic matter in pond sediments (Jimenez-Montealegre, 2001). This leads to sludge formation, anaerobic conditions, and the release of toxic compounds such as ammonia, nitrite, and hydrogen sulfide, which adversely affect survival, growth, and reproductive output (Avnimelech and Zohar, 1986; Boyd, 1995). Water exchange, though common in aquaculture, is impractical in *Artemia* ponds due to stock loss and operational constraints. *Artemia* are continuous filter feeders capable of consuming particles ≤50 μm. To ensure adequate feeding, chain raking is routinely practised in the pond bottom to resuspend settled particles, yet this practice also increases turbidity and organic decomposition. Therefore, science-based management approaches, such as probiotics, are essential to reduce organic load, improve water quality, and maintain a healthy pond environment that fosters optimal productivity of *A. franciscana*.

The decomposition of accumulated organic matter directly affects water quality, survival, and productivity in culture systems. Probiotics improve water quality by biodegrading uneaten feed and faeces (Tuan *et al*., 2013; Hura *et al*., 2018), accelerating mineralisation, producing extracellular enzymes, and reducing biological oxygen demand, thereby improving overall pond conditions (Wang *et al.,* 2008; Pennafirme *et al*., 2015). Beyond water improvement, probiotics enhance growth, reproduction, survival, and disease resistance in *A. franciscana* (Marques *et al*., 2006; Mathivanan *et al*., 2011; Thao *et al*., 2015). The study by Mahdhi *et al.* (2012) shows that halophilic *Bacillus* strains retain probiotic properties under high salinity and prolonged starvation, inhibit pathogenic *Vibrio* species, and improve *Artemia* survival under stress. As *Artemia* ponds are hyper-saline and nutrient-diluted environments, such salt-tolerant strains are particularly valuable in *Artemia* farming. Hence, regular probiotic application represents a preventive and sustainable approach to manage pond ecology, reducing organic load and stabilising microbial balance, which ultimately results in healthier *Artemia* populations and improved cyst yields. Among candidate probiotics, *Bacillus* sp. are widely used in aquaculture due to their spore-forming ability, which ensures stress resistance, heat tolerance, and long shelf life (Kuebutornye *et al*., 2019; Ghosh, 2025). They enhance feed utilisation, growth, stress tolerance, antioxidant and immune responses, water quality, reproduction, and disease resistance (Ghosh, 2025). *Marinobacter* sp., halophilic and non-pathogenic bacteria, also show probiotic potential because of strong antimicrobial activity (Jeganathan *et al.,* 2013) and efficient nitrogen removal in saline systems (Wang *et al.,* 2025). While *Bacillus* sp. tolerates 0–50 ppt salinity, *Marinobacter* sp. can withstand a much broader range of 0–180 ppt (Guo *et al*., 2025). Mahdhi *et al.* (2012) demonstrated the effect of probiotics on survival, stability, and disease protection under laboratory conditions, but did not replicate complex pond environments such as organic matter build-up, salinity fluctuations, stratification, anaerobic sludge formation, or assess cyst production and field performance across genera.

Most commercial probiotics are predominantly formulated for low-salinity aquaculture systems such as fish and shrimp ponds, highlighting the need to identify strains effective under high-salinity *Artemia* culture conditions. Therefore, the objective of the present study was to compare the efficacy of halophilic and halotolerant probiotics, *Marinobacter* sp. and *Bacillus* sp., in enhancing cyst productivity in *Artemia* culture systems. The findings demonstrated that the *Bacillus* sp. were more effective in maintaining pond conditions and enhancing cyst yield.

Material and methods

Experimental design

The experiment was conducted to evaluate the effect of probiotic application on pond performance and *Artemia* cyst production during two seasons of the year, *i.e.* winter (January–April) and summer (June – October). The study was conducted using three treatments, TR1, TR2 and Control. In TR1, ponds were treated with a *Bacillus*-based consortium (*Bacillus coagulans* and *Bacillus polymyxa*). TR2 ponds were treated with *Marinobacter* sp., and a control group (C) without probiotic addition served as the baseline for comparison.

Experimental ponds and pond preparation

The study was carried out at the RGCA *Artemia* Demonstration Farm, Uppoor, Ramanathapuram District, Tamil Nadu, India (9° 62′ 56.7′′ N, 78° 94′ 63.4′′ E) between June 2024 and April 2025. The experiment included 3 sections of the farm: BC section (Control), D section (TR1) and E section (TR2), each with a uniform water spread area of 1.62 ha to ensure comparability. The experimental ponds measured 0.09 ha in the BC section, 0.18 ha in the D and E sections. These ponds were originally constructed in 2015 and have been consistently used for *Artemia* cyst production over the decade. Before the experiment, all ponds were dried thoroughly, and shell lime was applied at a rate of 1,000 kg/ha. Each pond was then filled with bore water having a salinity range of 60–75 ppt, maintaining a depth of 30–40 cm (Lavens and Sorgeloos, 1996). Water quality parameters were measured before stocking to ensure uniform initial conditions (Fig. 1).

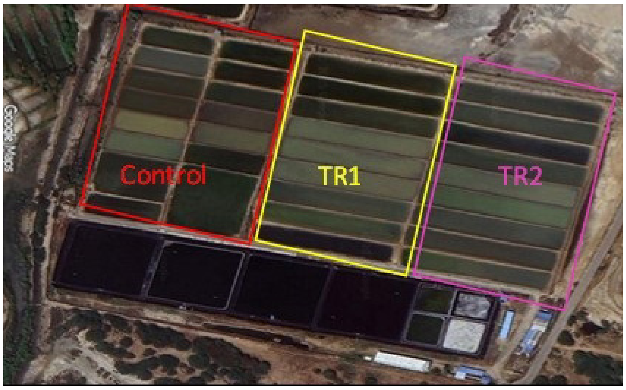

Fig. 1. Experimental ponds at RGCA *Artemia* demonstration farm, Uppoor

Probiotic selection

The choice of probiotic strains for this study was based on their proven efficacy in high-salinity aquaculture systems and their tolerance to extreme salinity levels under laboratory conditions. For Treatment 1 (TR1), a commercial probiotic X, a consortium of *B. coagulans* ($1x10^{10}$ cfu/g) and *B. polymyxa* ($1.2x10^{10}$ cfu/g) was used. These strains were selected based on their demonstrated role in maintaining water quality in high-saline shrimp culture ponds, as reported through farmer testimonials and prior field applications. Their ability to decompose organic matter and stabilise pond ecosystems made them suitable candidates for experimental evaluation. For Treatment 2 (TR2), another commercial probiotic Y, which has *Marinobacter* sp. ($3x10^9$ cfu/g), was used. This strain was originally isolated from solar salt farm environments and was found to exhibit an exceptional salinity tolerance ranging from 0 to 180 ppt during *in vitro* screening. Its halotolerance and adaptability to hypersaline ecosystems justified its selection as a probiotic treatment in this study. The control group (C) consisted of ponds without probiotic application, serving as a baseline for comparison.

Application of probiotics

The probiotic treatments were initiated on Day 0 of culture (DOC 0), one day before stocking, to condition the pond water and establish a beneficial microbial environment that enhances nauplii survival. For both treatment groups, the probiotics were applied once per week throughout the culture period. The initial dose was 2500 g/ha, followed by a maintenance dose of 1250 g/ha in subsequent applications until the end of the crop cycle. The probiotic X was mixed with pond water and applied to the culture ponds at 16:00 hours, whereas the microbial formulations of probiotic Y were activated by suspending the powder in molasses and incubating the mixture for 18–24 hours in aerated containers. The activated (probiotic Y) suspension was then broadcast into the ponds at 09:00 hours (as per the directions of the manufacturers). Immediately after application, raking was performed to ensure an even distribution of the microbial suspension throughout the pond water column.

Stocking and pond management

Artemia cysts were incubated at a density of 2 g L^{-1} in well-aerated cylindro-conical FRP tanks for 16–24 hours (Rajamani, 1998). Depending on the hatching synchrony, instar I nauplii were harvested in single or multiple batches to maximise survival potential. The nauplii were carefully counted and distributed equally to all the experimental ponds, ensuring a uniform stocking density of 80-100 nauplii/l. Upon inoculation, mixed microalgae (green algae and diatoms) were supplied to all ponds continuously at a flow rate equivalent to 5% of pond water volume (Rahman and Sorgeloos, 2023). In addition, supplementary feed was supplied to experimental ponds once per day based on the population density as required (Van Stappen *et al.,* 2024). The detailed feeding protocol is given in Table 1. After the maturation, cyst production was visually observed in the downwind corner in all experimental ponds, as *Artemia* cysts floated in the high saline water. From the onset of cyst and nauplii production (F1 generation), supplementary feed was provided to support sustained *Artemia* biomass growth and cyst yield.

Assessment of experimental parameters

Water quality parameters such as salinity, pH, and temperature were measured daily using handheld equipment; alkalinity and ammonia were measured by API kit (Mars Fishcare North America, Inc, USA) on a weekly basis to ensure that optimal environmental conditions for *A. franciscana* growth and reproduction were maintained throughout the culture period. Wet cysts were collected daily from each experimental pond

Table 1. Feeding protocol followed throughout the culture period (Van Stappen *et al.*, 2024)

DOC	Micro algae	Supplementary feed
1 to 20	Mixed microalgae dominantly with diatoms	Nil
20 to the end of culture	Mixed microalgae dominantly with diatoms	Supernatant of a mixture of fermented rice bran, ragi flour and molasses

using a 100 μm scoop net, cleaned and separated in 250 ppt saline water, weighed using a weighing balance and recorded.

Results

The treatment pond's water quality parameters, such as temperature, salinity, pH, alkalinity, nitrite and ammonia, were measured before the day of inoculation, and optimum parameters were maintained throughout the culture period. The application of commercial probiotics in *Artemia* culture ponds resulted in substantial improvements in *Artemia* cyst production compared to the untreated control ponds. The performance of the two commercial probiotics, probiotic X (*Bacillus*-based consortium) and probiotic Y (*Marinobacter* sp), was evaluated across two production cycles, winter crop (January – April) and summer crop (June – October). Considerable variation was observed in both total wet cyst yield and unit area production (kg/ha/crop).

Daily wet cyst yield

Upon inoculation in earthen ponds, *A. franciscana* reaches maturity, and F1 generation (both cyst/ nauplii) production commences. In the winter crop, cyst production commenced on DOC 13 in the control ponds (BC sections) and on DOC 16 in the treatment ponds (D and E sections). In contrast, during the summer crop, control ponds yielded cysts as early as DOC 08, while the treatment ponds produced cysts by DOC 10. The earlier onset of cyst production in the summer crop may be attributed to elevated ambient temperatures, which enhance the metabolic rate and reproductive activity of *A. franciscana*, thereby accelerating cyst formation. As the days of culture (DOC) progressed, the population steadily increased, resulting in a corresponding increase in cyst production. During the initial phase, cyst production was comparable across all ponds; however, a clear difference emerged as the culture advanced. In the control ponds, cyst production was low as DOC increased, whereas both probiotic-treated ponds maintained active production for an extended period. Daily cyst production trends for the winter and summer seasons are illustrated in Fig. 2 and 3, respectively.

In the winter crop, cyst production in the control ponds naturally ceased by 62 DOC, while both probiotic-treated

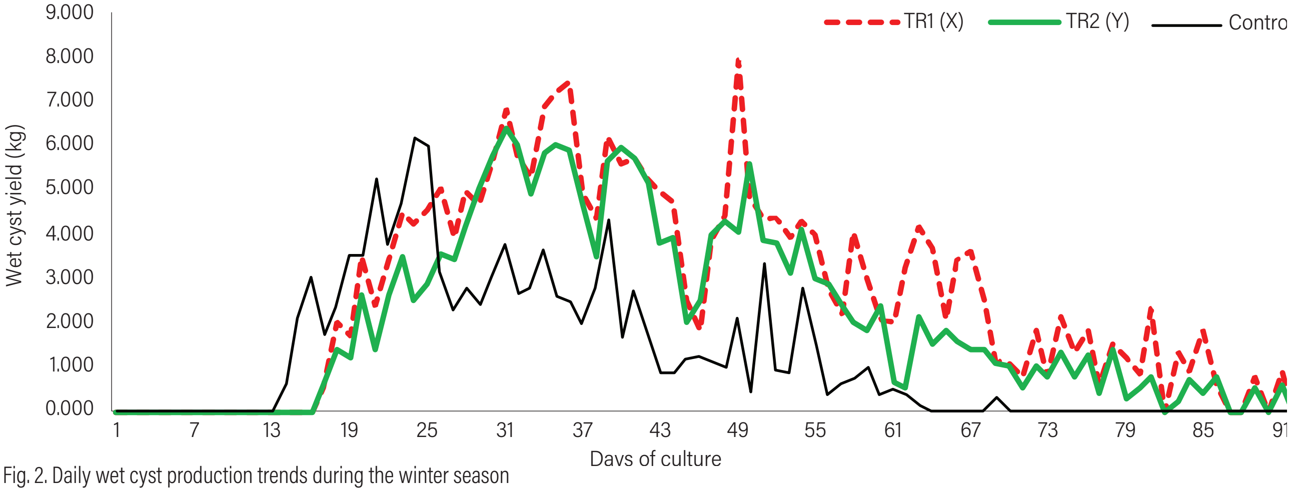

Fig. 2. Daily wet cyst production trends during the winter season

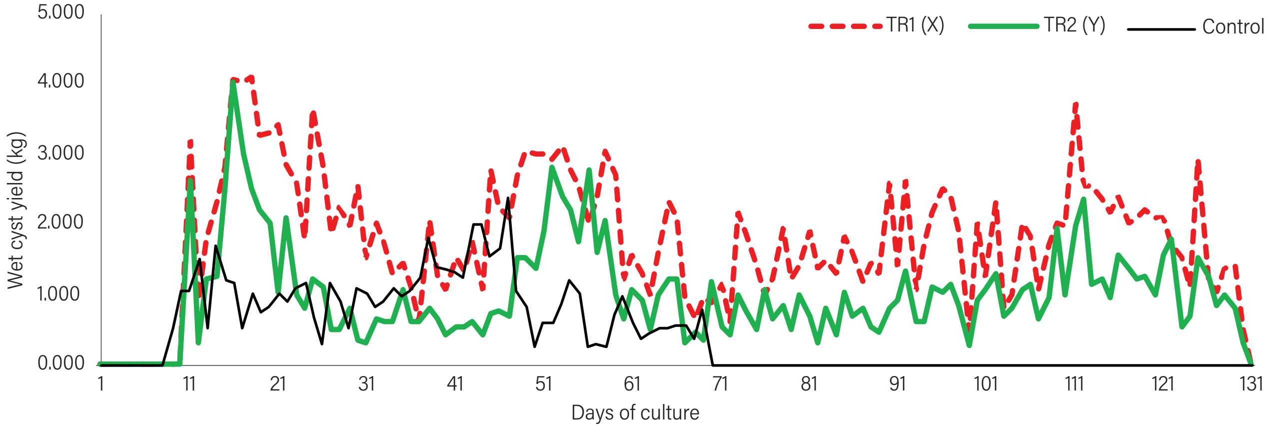

Fig. 3. Daily wet cyst production trends during the summer season

ponds continued producing cysts until 90 DOC. During the summer season, the control ponds ceased cyst production by 68 DOC, in contrast to the probiotic-treated ponds, which sustained production up to 129 DOC. This clearly demonstrates the positive impact of probiotic application in prolonging the reproductive phase of *A. franciscana* under hyper-saline pond conditions.

Unit area production

Unit area cyst production for the treatments and control is summarised in Table 2. During the winter season, TR1 (probiotic X) recorded the highest wet cyst yield of 240.520 kg, with a unit area yield of 148.470 kg/ha/crop. TR2 (probiotic Y) ponds produced 190.955 kg of wet cysts, corresponding to 117.870 kg/ha/crop. The control ponds recorded the lowest wet cyst yield of 112.19 kg, equivalent to 69.25 kg/ha/crop. TR1 (probiotic X) resulted in a 114% increase, while TR2 (probiotic Y) achieved a 70% improvement over the control.

During the summer season, TR1 (probiotic X) yielded the highest wet cyst yield of 232.615 kg, corresponding to 143.580 kg/ha/crop. TR2 (probiotic Y) ponds produced 130.330 kg or 80.450 kg/ha/crop wet cysts, while the control ponds recorded the lowest cyst yield of 57.635 kg, equivalent to 35.570 kg/ha/crop. Relative to the control, TR1 (probiotic X) delivered a remarkable 304% increase, whereas TR2 (Probiotic Y) showed a 126% improvement.

Table 2. Unit area production of the experimental farm during the winter and summer seasons of the year

Unit area cyst production (kg ha^{-1} crop^{-1})	TR1	TR2	Control
Winter (January – April)	148.470	117.870	69.250
Summer (June – October)	143.580	80.450	35.570

Overall, the winter crop outperformed the summer crop, consistent with typical *A. franciscana* production patterns. Across both seasons, TR1 (probiotic X) consistently delivered the highest cyst yield, outperforming both TR2 (probiotic Y) and the untreated control. The differences in unit area productivity among treatments were substantial, clearly indicating the beneficial role of *Bacillus*-based probiotic application on *A. franciscana* cyst production. Unit area production trends for the winter and summer seasons are illustrated in Fig.4.

Environmental parameters

Water quality parameters such as salinity, pH, and temperature were recorded daily. Other parameters, such as alkalinity and ammonia, were observed weekly. The average values in all experimental ponds are tabulated in Table 3.

The water temperature in all experimental ponds during the winter season ranged from 29-32 °C, while in summer it increased to 32-36 °C. This temperature variation showed a clear relationship with cyst yield. During winter, the consistently lower temperature supported higher cyst production, recording 240.52 kg in TR1, 190.955 kg in TR2, and 112.19 kg in the control ponds. However, the culture could not be extended

Table 3. Water quality parameters in experimental ponds during the winter and summer

HO Parameters	Winter			Summer		
	Control	TR1	TR2	Control	TR1	TR2
Temperature (°C)	31±0.75	31±0.95	31±0.81	32±0.53	33±0.84	33±1.03
pH	8.25±0.05	8.21±0.07	8.06±0.05	8.46±0.13	8.5±0.24	8.53±0.25
Salinity (ppt)	78±5.15	73±6.08	75±7.19	74±2.42	72±3.33	69±2.79
Alkalinity (mg/L)	100.87±6.16	91.25±5.23	97.49 ±6.98	113.87 ±5.16	92.54±6.06	98.69±5.96
Ammonia (mg/L)	0.806±0.09	0.172±0.05	0.258±0.03	0.921±0.06	0.137±0.08	0.278±0.09

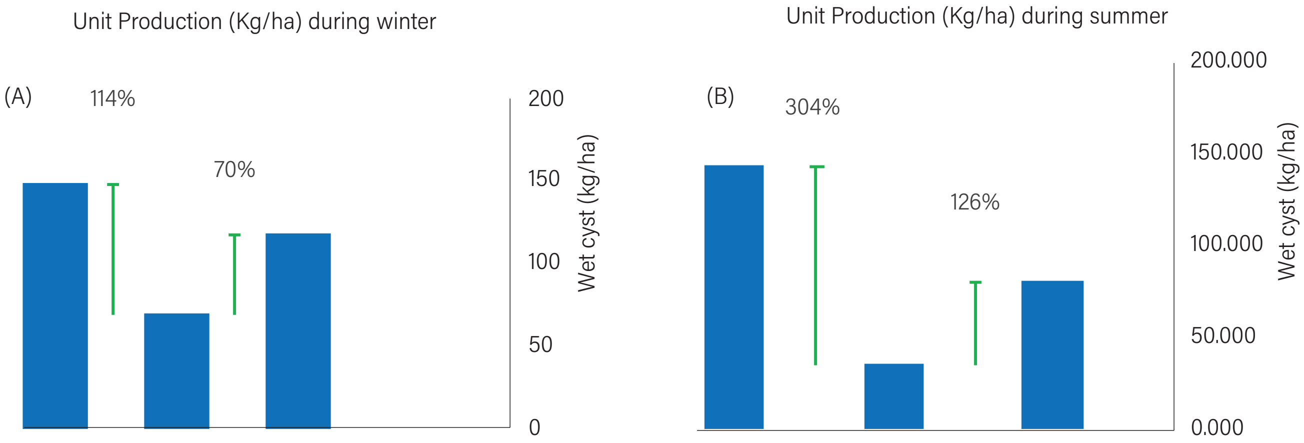

Fig. 4. Unit area production trends for the (A) winter and (B) summer seasons

beyond 90 days, as *A. franciscana* initially acclimated to lower temperatures (around 29 °C) and conditions exceeding 32 °C during that season were not favourable for its growth.

In contrast, summer cultures produced comparatively lower cyst yields, 232.615 kg in TR1, 130.330 kg in TR2, and 57.635 kg in the control. The initial inoculation temperature during this season was between 35-36 °C, and the culture duration extended up to 129 days within a temperature range of 32–36 °C. Even a slight increase in temperature was reflected in reduced cyst output, indicating the sensitivity of *A. franciscana* production to thermal fluctuations. The temperature profile throughout the culture is graphically represented in Fig. 5.

The pH values remained within favourable limits for *A. franciscana* culture, ranging from 8.0–8.25 during winter and 8.4–8.5 during summer. Salinity fluctuated between 60–75 ppt in winter and 60–85 ppt in summer. Alkalinity was consistently lower in TR1 ponds compared to TR2 and the control in both seasons (TR1 < TR2 < Control), which is attributed to the ability of the applied bacterial species to lower alkalinity through acid production during organic matter decomposition and nitrogen transformation. Ammonia levels were markedly lower in TR1 and TR2 ponds than in the control throughout both seasons. This reduction can be linked to the activity of *Bacillus* sp. and *Marinobacter* sp., which facilitate organic matter degradation along with nitrification and denitrification processes, thereby effectively minimising ammonia accumulation in the culture environment.

Discussion

Artemia culture systems tend to accumulate considerable organic waste due to uneaten feed particles, moults, and faecal matter. In addition, raking, a routine daily practice in *Artemia* ponds, causes vertical mixing of bottom sediments into the water column, further contributing to increased organic load. As a result, high concentrations of organic matter, nitrogen, and ammonia ultimately deteriorate the pond water quality of the *Artemia* ponds due to decomposition of organic matter. These poor water conditions negatively affect the survival and reproductive ability of the *A. franciscana*. To maintain suitable environmental conditions, various water-quality improvement methods have been developed for aquaculture. Among these, frequent water exchange is the widely used method for controlling metabolites in aquaculture (Crab *et al*., 2007; Martins *et al*., 2010; Jahangiri and Esteban, 2018). However, this method is not feasible for the *A. franciscana* culture. Consequently, the use of probiotics becomes a practical and effective alternative for improving pond water quality. Probiotics not only improve water quality (Jafaryan *et al,* 2011) but also offer other benefits to cultured animals (Zhao *et al*., 2009). Since water quality plays a key role in the growth and overall well-being of aquatic species, probiotic supplementation can help create more favourable culture conditions (Hura *et al*., 2018; Tuan *et al*., 2013). Reflecting their global importance, the probiotic ingredients market size was valued at USD 7.10 billion in 2024 and is projected to grow to USD 22.65 billion by 2034 (Swar, 2025).

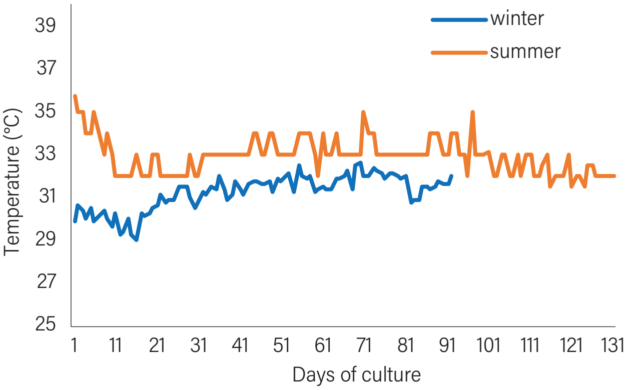

Fig. 5. Graphical representation of temperature fluctuations during winter and summer

A number of probiotic species have been evaluated for their effectiveness in aquaculture. Because *Artemia* is cultured in high saline environments, the selected bacterial strains must perform efficiently under halophilic conditions. In the present study, application of commercial probiotics significantly enhanced *A. franciscana* cyst production compared to the control ponds, emphasising the importance of microbial management in hyper-saline culture systems. The superior performance of the *Bacillus*-based consortium highlights its effectiveness in improving pond conditions, regulating organic matter, and promoting enhanced reproductive output. *Bacillus* sp. are well known for producing extracellular enzymes, degrading accumulated organic matter, rapidly colonising pond environments, stabilising pond micro-biota and reducing harmful metabolites such as ammonia, nitrite, and sulphides (Sedhiqi *et al*., 2025). The consistent improvement observed in TR1 indicates that *Bacillus* sp. effectively minimised bottom sludge formation, thereby supporting *A. franciscana* survival and cyst yield. Previous studies also confirmed the benefits of *Bacillus* in aquaculture systems. *Bacillus* consortium, including *B. polymyxa,* significantly reduced total ammonia nitrogen in carp pond effluents at an optimal dose of 10^8 CFU/l as an optimal amount of inoculum, while *Bacillus* supplementation at 1×10^6 CFU/l improved growth performance in grass carp through enhanced water quality or direct health benefits (Jafaryan *et al*., 2011). Verschuere *et al.* (2000) also noted that *Bacillus* sp efficiently outcompete other microbes due to their better nutrient utilisation.

The performance of probiotics was evaluated across two production cycles in winter (January-April) and summer (June-October) to assess the seasonal effectiveness under field conditions. Probiotic application significantly extended the reproductive period of the *A. franciscana* by maintaining favourable water quality parameters. As a result, cyst production persisted for a longer duration in probiotic-treated ponds, whereas production in control ponds declined and ceased earlier in both seasons due to progressive deterioration of water quality. Seasonal variation also influenced productivity. Cyst production started earlier in the summer crop compared to the winter crop. This earlier onset of cyst production during the summer crop may be attributed to elevated ambient temperatures, which enhance the metabolic rate and reproductive activity of *A. franciscana*, thereby accelerating cyst formation, as mentioned by Rahman and Jeyalakshmi (2009), that the production of cysts and biomass is directly related to the environmental temperature and salinity, supporting the observed seasonal differences in reproductive performance.

In the present study, probiotics-treated ponds exhibited better water quality than untreated control ponds, particularly in terms of ammonia. This improvement can be attributed to the nitrification capability of *Bacillus* sp. and *Marinobacter* sp., which convert nitrogenous waste generated during culture into less harmful forms. The TR1 ponds treated with a *Bacillus-based* consortium showed more effective ammonia reduction, resulting in higher cyst yield compared to control ponds. These findings align with those of Thao *et al.* (2015), who reported that the application of *Lactobacillus* and *Bacillus* lowered TAN levels and subsequently improved *A. franciscana* productivity, characterised by higher growth rates, mating rates, survival, and fecundity. Additionally, Thao and Nguyen (2014) reported that the application of *Bacillus* sp. in *A. franciscana* culture medium significantly improved fecundity and survival rates. Previous works, including those performed on laboratory scale (Mahdhi *et al.*, 2012; Thao and Nguyen, 2014; Thao *et al,* 2015), have also demonstrated that *Bacillus* can help to enhance survival, growth rate and fecundity, but viability or performance experiments were not conducted under commercial pond conditions. The current findings refine this understanding through the measurement of real production outcomes, a phenomenon that is rarely reported in the existing literature. The higher cyst yield of *Bacillus*-treated ponds at all times provides important field-based evidence for the practical application of *Bacillus* probiotics in *A. franciscana* operations.

Although *Bacillus* treatment resulted in the highest cyst production, the contribution of *Marinobacter* sp. remains noteworthy. Hu *et al.* (2021) described *Marinobacter* sp. as efficient degraders of organic pollutants, supporting nitrogen and phosphorus removal and thereby improving overall water quality. Similarly, Han *et al.* (2023) reported reduced ammonia levels in *Marinobacter-treated* systems. Correspondingly, the present study also recorded lower ammonia concentrations in ponds treated with *Marinobacter* sp., reaffirming its beneficial role in nitrogen regulation within *Artemia* culture ponds. Despite its halophilic adaptability and increasing recognition for wastewater treatment (Cheng *et al.*, 2025), the performance of *Marinobacter* in *Artemia* ponds was relatively lower than that of the *Bacillus*-based probiotic X. Nevertheless, *Marinobacter* treatment still resulted in improved cyst yields relative to the control. This comparatively lower performance may be attributed to slower growth kinetics of *Marinobacter*, as observed in laboratory conditions and possible competition with native halophilic microbiota. However, the 70% improvement over the control indicates that *Marinobacter* contributes positively to water quality and *A. franciscana* reproduction, albeit less efficiently than *Bacillus* sp.

The lowest yield recorded in control ponds highlights the challenges associated with *A. franciscana* culture in unmanaged microbial environments. Organic matter build-up and accumulation of toxic intermediates likely resulted in lower survival and diminished reproductive performance. Since *Artemia* reproduction is strongly influenced by environmental stress, the absence of microbial regulation in control ponds likely contributed to the reduced cyst yields.

Conclusion

Overall, the study confirms that effective microbial management plays a pivotal role in maximising cyst yield in *Artemia* production systems. The findings suggest that integrating effective probiotics, especially *Bacillus*-based formulations, into *Artemia* production systems can significantly increase cyst yield per unit area. This has significant implications for regions like India, where demand for *Artemia* cysts continues to rise, and domestic production remains insufficient. This study demonstrates that *Artemia* cyst productivity can be enhanced through the combined application of suitable probiotics during the culture period, offering a pathway toward more sustainable and efficient production. Although previous studies have highlighted the use of probiotics and their positive effect in improving survival and growth performance, they lack field testing. Therefore, the current work bridges the gaps between laboratory and field by providing a first-of-its-kind field-level, industrially salinised, multi-probiotic comparison directed to augmenting the productivity of *Artemia* cysts in order to improve both scientific knowledge and application-driven aquaculture output.

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Author contributions

Conceptualisation: MS; Methodology: MS; Data Collection: NVR; Data Analysis: MS, AAM; Writing original draft: AAM, MS, GS; Writing Review and Editing: MK, AAR; Supervision: SK, MS, MK.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Data availability

The data are available and can be requested from the corresponding author.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ the collection of sensitive samples/ protected environments.

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Co-occurrences of jellyfish in the shrimp fishing grounds of Palk Bay and the Gulf of Mannar and their implications in the commercial fishery

M. Rajkumar*, S. Thirumalaiselvan, R. Saravanan, K. Shanmuganathan, A. K. Abdul Nazar and Shoba Joe Kizhakudan
ICAR-Central Marine Fisheries Research Institute, Kochi-682 018, Kerala, India.

*Correspondence e-mail: rajkumar.m@icar.org.in
ORCiD: https://orcid.org/0000-0001-6394-5464

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Original Article

Abstract

The regular abundance of jellyfish in Palk Bay and the Gulf of Mannar during the Indian summer was studied in 2023. Experimental bottom trawling was carried out to assess the influence of jellyfish on fish and shrimp catches in the shrimp fishing grounds of the Gulf of Mannar and Palk Bay. The jellyfish that were caught in the gear were measured and quantified. Among fin fishes, about seven species of silverbellies were more prevalent in both regions' catches. In Palk Bay, *Lobonemoides robustus* is a common jellyfish, whereas three other jellyfish species were also found in the Gulf of Mannar, including *Cyanea nozakii*, *Rhopilema hispidum*, and *Chrysaora chinensis*. *C. nozakii* was shown to be the dominant and most numerous species in the Gulf of Mannar region. Using morphometric data, the relationship between bell diameter and weight for these jellyfish was determined. In general, the perception of fishermen is that there is less fish catch in the jellyfish areas, but in our experiment, the shrimp catch was normal despite the jellyfish abundance. Continuous monitoring can help to demarcate jellyfish occurrence areas as Jellyfish Focal Areas (JFA) for better management of commercial fishing operations in both the Gulf of Mannar and Palk Bay.

Keywords: *Jellyfish focal areas, shrimp fishery, bottom trawl, catch rate*

Introduction

The Gulf of Mannar and Palk Bay lie between India and Sri Lanka. Palk Bay is situated on the southeast coast of India, encompassing the sea between Point Calimere in the north and Dhanushkodi in the south (Kumaraguru *et al*., 2008). The Gulf of Mannar encompasses the territorial waters from Dhanushkodi in the north to Kanyakumari in the south (Kumaraguru *et al*., 2006). Jellyfish inhabit the world's oceans and estuaries, ranging from the surface to the deepest depths. Jellyfish swarms are widespread and frequent in coastal areas worldwide, and they are considered a menace due to their ecological and socioeconomic consequences (Stabili *et al*., 2020). During the pre-monsoon, an increase in temperature, along with a rise in salinity, favours the blooming of jellyfish in the coastal waters and adjacent estuarine and backwater areas along the southern Indian coastline.

Trawl fishing attempts in Palk Bay began in the twentieth century (Herdman, 1903). Palk Bay's shrimp fishery has grown since 1980 into a major industry that supports the largest coastal fisherfolk population along the Tamil Nadu coast. The green tiger shrimp, *Penaeus semisulcatus,* was the major species contributing to the shrimp fishery along the Mandapam coast of Palk Bay and Gulf of Mannar (Thomas, 1974; 1975). In the nineties, fishing vessels with a length range of 9.15–9.76 m and an engine power of 41–88 hp were commonly operated in Palk Bay (Maheswarudu *et al*., 1996; Krishnan, 2012). Due to increasing demand and fishing pressure, the overall length of the fishing vessel has increased to 18 m with 180 hp (Rajkumar *et al*., 2022). In Palk Bay only single-day fishing patterns are followed, and the cod end mesh size of the trawl net is maintained at 25 mm, which is contrary to the prescription of the Marine Fishing Regulation Act, 1983.

Jellyfish harm the fisheries sector. The jellyfish menace led to lower catches of *Metapenaeus dobsoni* in the estuarine stake nets operated off Kochi, Kerala (Sandhya *et al.*, 2020). Scyphozoan jellyfish are generally known to affect the fishing industry, tourism, aquaculture, and pumping machinery (Richardson *et al.*, 2009). Some jellyfish can also have ecosystem impacts, such as indirect effects on fisheries resources (Purcell *et al.*, 2007). *Chironex indrasaksajiae*, a deadly species of box jellyfish, causes severe sting scars (Saravanan *et al.*, 2024), and the extremely venomous genus *Chironex* has occasionally caused deaths in tropical and subtropical coastal regions across the globe. Despite this, jellyfish are important in stabilising the marine ecosystem by supporting nutrient cycling (Lebrato *et al.*, 2012) and establishing symbiotic relationships with fish (Purcell and Arai, 2001). Carangid juveniles live in harmony with scyphozoan jellyfish (Rajkumar *et al.*, 2014), and the survival rate of juveniles of some pelagic fish species depends on jellyfish in a big way, since pelagic fish rarely eat young individuals of these species that are associated with jellyfish (Nagabhushanam, 1964).

Most species of jellyfish lack commercial value due to non-consumption, but in recent years, reports from Sri Lanka and India have indicated export of processed bells and oral arms of *Crambionella* species, *Lobonemoides, Catostylus perezi* and *Rhopilema hispidum* to South Asian countries (Kumawat *et al.*, 2023; Karunarathne *et al.*, 2024). Some other species, like *Cassiopea andromeda*, are used in aquaria and zoos (Karunarathne *et al.*, 2020). Traditional trap fisheries operating along the same coastline used species like *Acromitus flagellatus* and *Lychnorhiza malayensis* as live baits to capture demersal fish species (Karunarathne *et al.*, 2021).

Huge jellyfish entrapment hinders shore-seine fishing activity in Palk Bay and the Gulf of Mannar, where fishermen employ manual labour to drag their nets. This causes considerable economic loss to fishermen operating the shore seine for shoaling fish, and they invariably get jellyfish in their nets during these swarming months (Saravanan *et al.*, 2016). The scyphozoan jellyfish most often reported in the coastal waters of Palk Bay and the Gulf of Mannar include *Mastigias papua, Netrostoma coerulescens, Cassiopea xamachana, Chrysaora caliparea,* and *Rhopilema hispidum*. The present study aims to investigate jellyfish co-occurrences in the shrimp fishing grounds of Palk Bay and the Gulf of Mannar, as well as their implications on the commercial fishery.

Material and methods

Experimental bottom trawling was conducted in two locations *viz.*, the Gulf of Mannar on June 6, 2023, and Palk Bay on June 9, 2023, in the shrimp fishing grounds (Fig. 1) with two hauls

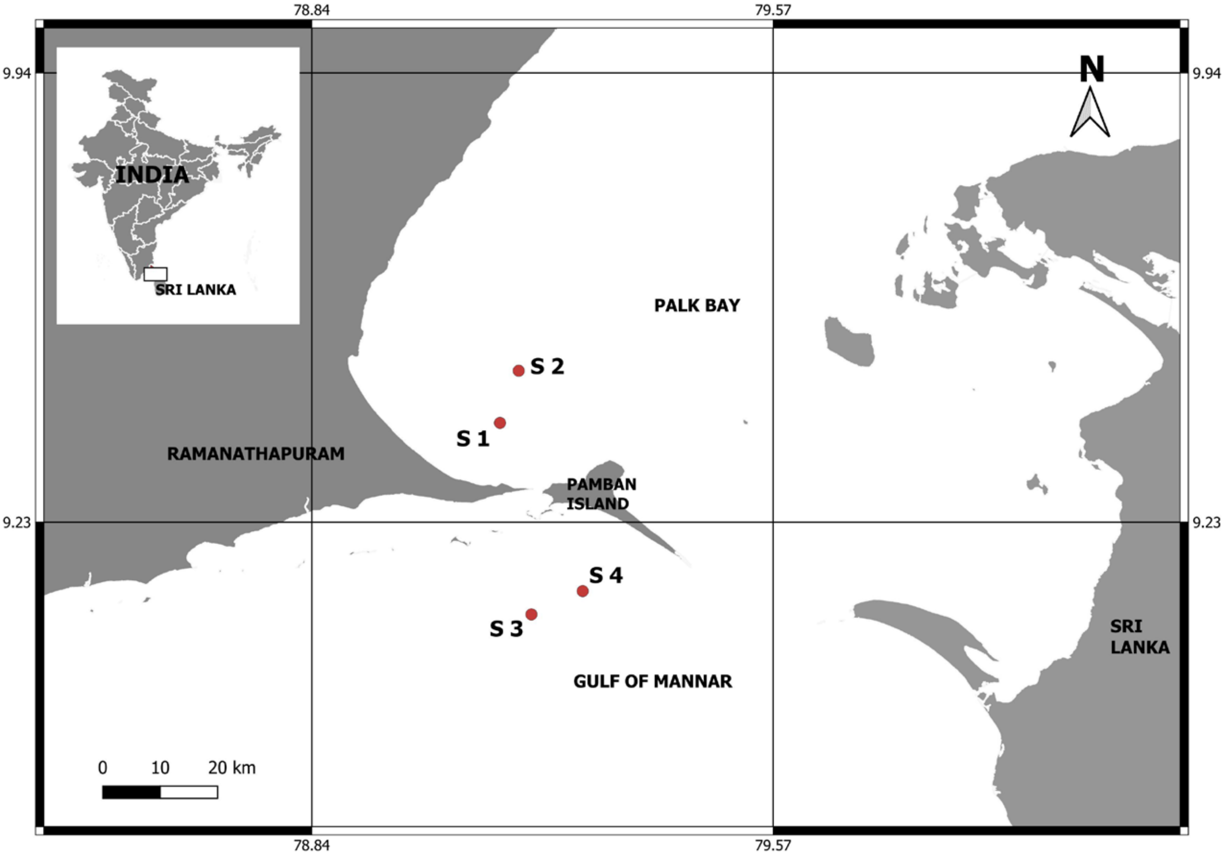

Fig. 1. Sampling locations (red dotted) in the Palk Bay and Gulf of Mannar

in each location to assess the co-occurrence of jellyfish. An onboard GPS (GARMIN 420 S) was used to locate and record the sites during the study. A trawl net with 20 mm cod-end mesh was used during the experimental trawl fishing operation. The standard operating procedure was followed for the shooting and hauling of nets during the entire fishing operation. The specifications of the trawler (stern bottom trawler) and trawl net (shrimp trawl attached to an otter board) used for experimental fishing are provided in Table 1. The primary species targeted in both areas was the shrimp *Penaeus semisulcatus*. Each haul went for 120 min in the Gulf of Mannar and Palk Bay. The catches were segregated, and the species were identified. The jellyfish caught in the gear were measured and weighed.

The biomass quantification of jellyfish was done by the swept area method using the following formula (Sparre and Venema, 1992).

$$a = D * h * X_2$$

where, 'a' is the swept area in square nautical miles (NM^2), 'D' is the distance covered by trawl in NM (calculated using exact positions of the start and end of the haul), 'h' is the length of the head-rope (30 m), 'X_2' is the fraction of the head-rope length or wing spread ratio (0.4 to 0.6 for Southeast Asian bottom trawls but optimum 0.5 was taken for the study). The biomass is estimated as follows (Sparre and Venema, 1992)

$$b = \frac{\frac{(cw}{a)}}{X_1}$$

where, 'b' is the biomass kg/NM^2, 'a' is the area swept by trawl, 'cw' is the catch in weight of a haul (in Kg), X_1 is the fraction of the biomass in the effective path swept by trawl, which is retained in the gear

The length-weight relationship (LWRs) and condition factor were also derived for some of the jellyfish using the formula given by Le Cren (1951),

$$W = aL^b$$

Table 1. Specifications of trawler and trawl net used for experimental fishing

Craft details		Gear details	
Craft type	Trawl	Gear type	Trawl net
Overall length	12 m	Head rope length	65 m
Beam	3.5 m	Foot rope length	70 m
Draft	2.0 m	Otter board type	Rectangular and flat
Power	120 hp	Length of trawl net	37 m
		Cod end Mesh size	20 mm

where W = total weight in grams, L = Bell diameter in centimetres, and 'a' and 'b' are the allometric growth constants.

The correlation coefficient 'r' was calculated to determine the strength and pattern of association between the two variables. The condition factor was calculated by the formula (LeCren, 1951),

$$K = W/(aL^b)$$

where, K = Condition factor, W = Weight (g), L = Bell diameter (cm), 'a' and 'b' are constants.

Results and discussion

The jellyfish catch first and second hauls in the Gulf of Mannar were 350 kg and 90 kg respectively, and the catch rate was 73 kg per hour. The biomass of jellyfish was estimated to be between 106 and 416 kg/NM^2 for the first and second hauls. The average biomass was 211 kg/NM^2. In Palk Bay, the jellyfish catch in the first and second hauls were 32 kg and 43 kg respectively, and the catch rate was 12.5 kg per hour. The biomass of jellyfish was estimated to be 41 and 208 kg/NM^2 for first and second hauls, respectively. The average biomass was 69 kg/NM^2.

In both regions, among the 35 varieties of finfish resources (Table 2), silverbellies were more abundant in the catch. In the Gulf of Mannar, the catch rate of *P. semisulcatus* was 6.3 kg/h, and three species of jellyfish, *viz. C. nozakii*, *R. hispidum*, and *C. chinensis,* were found in the depth range of 22–24 m (Fig. 2

Table 2. Species recorded in the experimental trawling

Groups	Species	Size range (TL) (mm)	weight range (g)	Biomass (kg)	Catch (%)
Teleost	*Alectis indica*	73-105	1.93-55.62	0.43	0.10
	Alepes kleinii	50-134	1.6-45	0.11	0.03
	Apistus carinatus	64-87	4.5-10.85	0.15	0.04
	Jaydia ellioti	73	8.35	0.01	0.00
	Arothron immaculatus	266	305	0.34	0.08
	Bathycongrus nasicus	237-340	9.72-29.84	0.10	0.02
	Carangoides coeruleopinnatus	125	48.07	0.05	0.01
	Cirrhitichthys bleekeri			0.00	0.00
	Cynoglossus arel	235-292	70.82-146.87	1.08	0.26
	Cynoglossus dispar	41-230	2.03-20.58	0.53	0.13
	Cynoglossus puncticeps	64-101	3.06-8.82	0.03	0.01
	Epinephelus areolatus	141	38.62	0.04	0.01
	Gazza minuta	80-139	10.18-39.44	8.74	2.11
	Gerres longirostris	91-131	15.52-63.79	0.36	0.09

Groups	Species	Size range (TL) (mm)	weight range (g)	Biomass (kg)	Catch (%)
	Heteromycteris oculus	76-99	4.66-11.88	0.02	0.00
	Hilsa kelee	140	31.77	0.03	0.01
	Johnius borneensis	11-109	2.03-23.6	0.21	0.05
	Karalla daura	95-120	2.59-26.6	0.36	0.09
	Karalla dussumieri	54-125	1.25-53.87	109.36	26.44
	Lactarius lactarius	204	93	0.10	0.02
	Lagocephalus lunaris	90-176	16.19-130.47	0.16	0.04
	Equulites lineolatus	12-110	0.18-40.1	6.74	1.63
	Lepturacanthus savala	49-146	2.63-39.53	0.69	0.17
	Lethrinus lentjan	101-370	15.94-460	3.95	0.96
	Leucosia anatum	9-18	1.73-5.04	0.06	0.01
	Ellochelon vaigiensis	145-156	36.94-46.32	0.18	0.04
	Lutjanus fulviflamma	190	100.75	0.11	0.03
	Lutjanus lutjanus	110	20.35	0.02	0.01
	Muraenesox bagio	501	121.58	0.13	0.03
	Nemipterus japonicus	102-163	19.06-69.61	1.01	0.24
	Netuma thalassina	349	448	0.49	0.12
	Nibea maculata	122-172	42.22-92.11	0.24	0.06
	Nuchequula gerreoides	21-116	3.76-41	4.08	0.99
	Otolithes ruber	117	14.33	0.02	0.00
	Pampus chinensis	155.0	177.0	0.19	0.05
	Parastromateus niger	75-152	12.28-116.95	0.61	0.15
	Pelates quadrilineatus	60-173	5.24-78.23	0.45	0.11
	Pellona ditchela	21-134	8-29.16	0.20	0.05
	Paramonacanthus nipponensis	81	12.81	0.01	0.00
	Photopectoralis bindus	95	15.49	0.02	0.00
	Platycephalus indicus	51-195	2.32-66.01	0.78	0.19
	Plotosus lineatus	65-132	1.77-13.61	2.67	0.64
	Psettodes erumei	80-170	10.27-62.38	0.23	0.05
	Pseudorhombus elevatus	71-77	4.59-5.72	0.01	0.00
	Pseudorhombus malayanus	32-105	1.26-40.72	19.94	4.82
	Pseudorhombus triocellatus	92-113	13.68-22.92	1.61	0.39
	Pterois russelii	130-183	31.86-88.06	0.13	0.03
	Rastrelliger kanagurta	75	3.37	0.00	0.00
	Richardsonichthys leucogaster	64-95	7.86-16.25	0.06	0.01
	Sardinella albella	129-134	23.48-25.15	0.05	0.01
	Saurida micropectoralis	11-275	9.53-148.04	3.13	0.76
	Scomberoides commersonnianus	201	64.01	0.07	0.02
	Scomberomorus commerson	140-203	21.8-60.55	0.53	0.13
	Leiognathus ruconius	80-139	10.18-39.44	23.07	5.58
	Selaroides leptolepis	11-151	9.25-38.52	2.86	0.69
	Siganus canaliculatus	60-162	10.39-72.91	0.70	0.17
	Sillago sihama	75-204	3.67-124.06	1.72	0.42
	Sphyraena pinguis	125-273	53.71-135.8	0.30	0.07
	Sphyraena flavicauda	190-220	59.2-72.46	0.21	0.05
	Stolephorus commersonnii	51-125	1.64-16.28	0.20	0.05
	Stolephorus indicus	49-76	0.99-3.97	0.09	0.02
	Strophidon sathete	555	75.73	0.08	0.02
	Telatrygon zugei	119-199	28.72-265	1.62	0.39
	Terapon puta	17-125	4.66-91.12	2.21	0.53
	Thryssa mystax	60-146	1.59-31.82	1.16	0.28
	Thryssa setirostris	76-178	3.41-17.7	0.17	0.04
	Trachinocephalus myops	71-231	3.62-57.35	0.71	0.17
	Trypauchen vagina	141	38.62	0.01	0.00
	Upeneus sundaicus	60-190	10.01-61.15	10.36	2.51
	Upeneus tragula	95-172	12.58-64.8	1.70	0.41
	Upeneus margarethae	95-172	12.58-64.8	3.69	0.89
	Scomberomorus commerson	39-55	200-300	0.50	0.12
Elasmobranchs	*Brevitrygon imbricata*	71-272	13.99-226	0.77	0.19
	Gymnura poecilura	246-277	131.96-209.42	0.38	0.09
	Torpedo sp.	70	27.36	0.03	0.01
	Glaucostegus granulatus	276-291	63.69-72.44	0.15	0.04
Cephalopods	*Uroteuthis (Photololigo) duvaucelii*	78	29.71	0.03	0.01
Shrimps	*Alpheus lobidens*	44-60	2.51-4.06	0.02	0.00
	Metapenaeopsis barbata	60	2.4-3.77	0.01	0.00
	Metapenaeopsis stridulans	54-67	1.66-3.01	0.02	0.01
	Metapenaeus moyebi	59-95	1.31-6.84	0.05	0.01
	Kishinouyepenaeopsis maxillipedo	35-94	4.23-14.68	1.59	0.38
	Penaeus indicus	75	2.64	0.00	0.00
	Penaeus latisulcatus	105-135	8.84-23.47	0.06	0.01
	Penaeus semisulcatus	22-222	8.29-90.9	12.32	2.98
	Megokris granulosus	45-166	1.02-5.68	0.18	0.04
Crabs	*Aethra scruposa*	74	54.01	0.06	0.01
	Albunea occulta	23	4.5	0.00	0.00

Groups	Species	Size range (TL) (mm)	weight range (g)	Biomass (kg)	Catch (%)
	Arcania erinacea	2-5	4-5	0.04	0.01
	Arcania heptacantha	18	5.43	0.01	0.00
	Calappa bilineata	46-90	16.19-137.8	0.76	0.18
	Calappa clypeata	35	6.26	0.01	0.00
	Calappa gallus	36	14.65	0.02	0.00
	Calappa lophos	34-65	7.35-85.98	0.80	0.19
	Charybdis (Charybdis) natator	44-66	20.27-102.97	0.28	0.07
	Charybdis (Charybdis) variegata	36	14.65	0.02	0.00
	Charybdis (Charybdis) granulata	22-25	1.86-2.72	0.01	0.00
	Doclea canalifera	20-35	1.31-16.14	0.06	0.01
	Dorippe frascone	10-22	1.91-4.77	0.02	0.00
	Dorippe quadridens	20-31	3.21-11.67	0.05	0.01
	Enoplolambrus pransor	19-28	7.93-14.54	0.08	0.02
	Ixa cylindrus	19-51	0.54-4.78	0.05	0.01
	Matuta planipes	10-26	1.95-13	0.04	0.01
	Myra fugax	16-25	3.38-5.06	0.04	0.01
	Pagurus kulkarnii	20-110	0.73-29.41	0.53	0.13
	Portunus pelagicus	50-70	110-150	0.43	0.10
	Eodemus hastatoides	19-34	1.02-8.21	0.20	0.05
	Portunus sanguinolentus	10-54	18-115	5.62	1.36
	Monomia gladiator	17-71	1.02-49.8	0.59	0.14
Stomatopods	*Cloridopsis immaculata*	55-94	2.28-48	0.09	0.02
	Erugosquilla woodmasoni	64-169	2.73-46.73	0.29	0.07
	Oratosquillina gravieri	35-127	1.04-90.04	1.07	0.26
	Oratosquillina quinquedentata	45-96	1.47-7.77	0.23	0.06
Gastropods	*Babylonia spirata*	34-51	4.76-24.81	0.45	0.11
	Babylonia zeylanica	22-46	2.17-21.64	0.05	0.01
	Bufonaria crumena	20-75	1.14-32.55	0.60	0.15
	Chicoreus virgineus	28-64	2.38-21.76	0.04	0.01
	Conus amadis	31-45	2.94-9.11	0.02	0.01
	Conus araneosus	41-51	8.72-23.45	0.07	0.02
	Conus monile	38	7.61	0.01	0.00
	Hastula raphanula	37	2.4	0.00	0.00
	Ficus ficus	63-67	12.9-79	0.14	0.03
	Fusinus colus	62	2.93	0.00	0.00
	Gemmula vagata	30-69	1.0-11.59	0.05	0.01
	Gyrineum natator	42	5.77	0.01	0.00
	Harpa major	65-79	36.54-49.19	0.15	0.04
	Unedogemmula indica	55-90	4.79-11.57	0.12	0.03
	Neodilatilabrum marginatum	27-49	1.31-11.25	0.04	0.01
	Monetaria annulus	42	5.77	0.01	0.00
	Murex tribulus	22-70	0.9-10.11	0.07	0.02
	Nassaria pusilla	15-26	0.83-2.59	0.03	0.01
	Nassarius glans glans	39	2.92	0.00	0.00
	Nassarius stolatus	28-32	1.18-4.35	0.01	0.00
	Naticarius canrena	20-24	1.8-2.79	0.01	0.00
	Tanea picta	15-18	1.63-2.15	0.00	0.00
	Natica vitellus	16	0.78	0.00	0.00
	Neverita didyma	30-45	5.83-17.41	0.10	0.02
	Notocochlis gualteriana	19	2.61	0.00	0.00
	Oliva reticulata	29-49	2.84-12.83	0.21	0.05
	Oliva sericea	19-46	0.57-11.03	0.11	0.03
	Phalium glaucum	29-68	4.04-91.79	0.55	0.13
	Polinices mammilla	7-8	1.43-1.5	0.00	0.00
	Mammilla melanostoma	22-23	1.4-1.41	0.00	0.00
	Rapana rapiformis	19-65	1.66-34.5	0.25	0.06
	Semicassis bisulcata	34-45	3.86-11.51	0.03	0.01
	Tanea lineata	15-25	0.97-2.59	0.01	0.00
	Tonna dolium	14-97	0.21-58.33	0.56	0.13
	Turbinella pyrum	29-111	1.44-175.72	0.59	0.14
	Turritella terebra	79	12.73	0.01	0.00
	Vexillum acuminatum	24-25	0.94-1	0.00	0.00
	Volegalea cochlidium	29-97	1.64-152.18	0.65	0.16
Bivalves	*Tegillarca granosa*	36	6.44	0.01	0.00
	Anadara inaequivalvis	9-34	0.73-14.62	0.94	0.23
	Cardites bicolor	8-26	1.32-8.04	0.16	0.04
	Cucullaea labiata	22-58	3.64-51.54	1.33	0.32
	Latona cuneata	11-33	0.35-2.49	0.01	0.00
	Donax faba	19-34	1.02-4.18	0.01	0.00
	Donax incarnatus	6-11	0.47-1.32	0.00	0.00
	Marcia opima	25	6.1	0.01	0.00
	Meretrix casta	9-56	0.44-40.17	0.92	0.22
	Paratapes textilis	8	2.34-2.31	0.01	0.00
	Pinctada fucata	32	4.25	0.00	0.00
	Pinctada sugillata	33	2.6	0.00	0.00
	Pinna bicolor	141	4.91	0.04	0.01
	Placuna placenta	14-79	0.18-8.08	0.17	0.04

Groups	Species	Size range (TL) (mm)	weight range (g)	Biomass (kg)	Catch (%)
	Solen strictus	51	1.16	0.00	0.00
	Macomangulus tenuis	22	2.46	0.00	0.00
	Vepricardium asiaticum	14-46	1.27-25.57	0.49	0.12
	Volachlamys tranquebaria	27-33	1.77-4.25	0.01	0.00
Echinoderms	*Brissus unicolor*	55-64	11.35-34.98	0.05	0.01
	Sculpsitechinus auritus	35-94	4.23-14.68	0.07	0.02
	Salmacis virgulata	14-87	1.05-49.81	0.20	0.05
	Ophiactis savignyi	45-50	1.1-5.2	0.01	0.00
	Archaster typicus	29-170	1.12-11.71	0.07	0.02
Barnacles	*Balanus*	11-16	0.29-0.39	0.00	0.00
Jellyfish	*Cyanea lamarckii*	105-490	110-7400	142.26	34.39
	Rhopilema hispidum	140-210	180-506	4.96	1.20
	Chrysaora chinensis	46-112	15-65	0.31	0.08
	Lobonemoides robustus	45-215	30-560	7.21	1.74
	Sponge	61-115	14.97-62.64	0.42	0.10
	Chank egg	11	1.1	0.00	0.00

and Fig. 3). Among these, *C. nozakii* was found to be the dominant and most abundant species in the Gulf of Mannar region. In Palk Bay, very minor quantities of shrimp (0.9 kg/hour) and jellyfish were caught at 10 m depth. *L. robustus* is an abundant jellyfish in this area. (Fig. 4). The Sea Surface Temperature (SST) and salinity recorded were in the range of 28.6-30.2 °C and 33-34 ppt in the fishing grounds of Palk Bay and the Gulf of Mannar. The size distribution of jellyfish in the Gulf of Mannar and Palk Bay is depicted in Fig. 5, and the length-weight relationship of jellyfish is depicted in Fig. 6. The morphometric values of jellyfish are given in Table 3. The relationship between bell diameter and wet weight was highly significant ($r^2>0.9$; $p<0.01$) for *C. nozakii*, *C. chinensis,* and *L. robustus*.

The seasonal fishing ban on the east coast starts from April 15th to June 14th to avoid the breeding season of most of the fishery resources of this coast. After the ban, shrimp fishing is at its peak in both the Palk Bay and the Gulf of Mannar region. This preliminary study determined the influence of jellyfish co-occurrences in the shrimp fishery. Jellyfish play a vital role in the ecosystem. Lynam and Brierley (2007) said that young (0-group) gadoid fish that have been hiding under the umbrellas

Fig. 2. Jellyfish caught in trawl in the Gulf of Mannar (haul-1). A. Unloading of catch from the cod end, B. Catch, C. Sorting of catch and measuring jellyfish

Fig. 3. Jellyfish caught in trawl in the Gulf of Mannar (haul-2). A. Catch, (Arrow shows jellyfish) B. *Cyanea nozakii*

Fig. 4. Experimental trawl catches in Palk Bay. A. Catch (haul-1, arrow shows jellyfish), B. Sorting of the catch onboard, C. Holding a specimen of *Lobonemoides robustus,* D. Catch (haul-2)

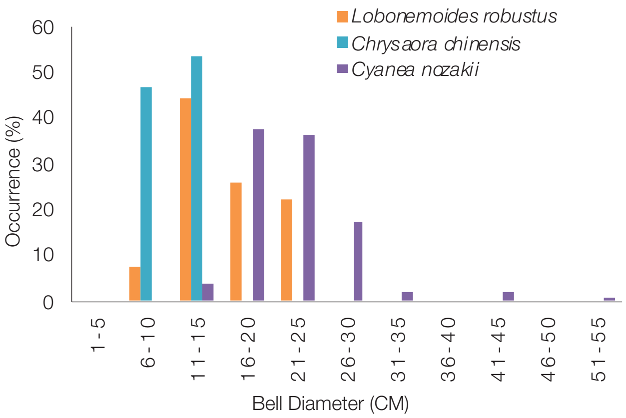

Fig. 5. Size distribution of Jellyfish catches in the Gulf of Mannar and Palk Bay

of scyphozoan and hydrozoan jellyfish may find safety from predators by hiding among the tentacles of medusae. This would help the survival of juvenile gadoids where there are lots of medusae. Most trawl fisheries discard most of the caught species, with estimates of the ratio of bycatch and discards to the total catch ranging from 45 to 50% (Tudela, 2004). According to Bailey (1989), large-sized jellyfish accounted for 86.9% of the weight of midwater trawl catches, with juvenile Pollock coming in second (11.6%). A moon jellyfish affects the size distribution and catches efficiency of horse mackerel in the midwater trawl fishery of the Black Sea. It has been found that moon jellyfish make up 33% of the total catch (Özdemir, 2014).

According to a study by Behera *et al.* (2022), the relationship between length (diameter) and weight is negative allometry for *Crambionella annandalei* (b = 2.547–2.601) and *Chrysaora* spp. (b = 2.34–2.981). The present study also recorded similar results with b values less than three and showed negative allometry for *C. nozakii* (2.402), *C. chinensis* (1.556), and *L. robustus* (2.043).

Generally, fishermen perceive 1–3 kg of green tiger shrimp per hour of operation as good in normal circumstances, however when jellyfish co-occurs; the catch is reduced, but our experimental trawl revealed a normal shrimp catch despite the jellyfish abundance, mainly because of the ban on commercial fishing operation and our experimental fishing is done with special permission to assess jellyfish abundance in shrimp fishing ground during the ban period. The experimental trawling data show that the Palk Bay and Gulf of Mannar shrimp catches differed during the same period. Rajkumar *et al.* (2023; 2024) asserted that the higher shrimp catch rates in Palk Bay were attributed to its productive fishing grounds, which are relatively shallow, whereas fishing in the Gulf of Mannar occurs in comparatively deeper waters. However, in the present investigation, the catch is higher in the Gulf of Mannar than in Palk Bay due to the ban period and monsoon changeover period. Jellyfish are a free-swimming medusa stage and mostly distributed in the pelagic

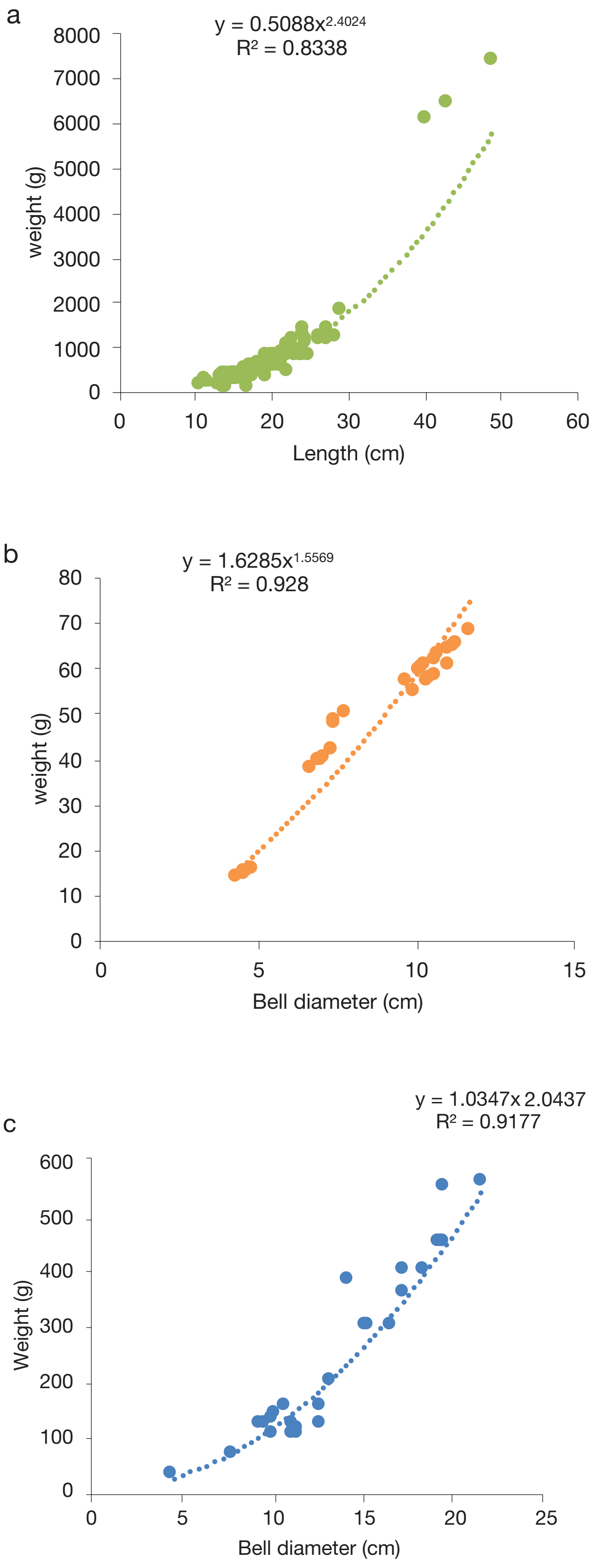

Fig. 6. Length-weight relationship of Jellyfish in the Gulf of Mannar and Palk Bay. A. *Cyanea nozakii,* B. *Chrysaora chinensis* C. *Lobonemoides robustus*

Table 3. Morphometric values and condition factor of the jellyfish

Species	n	Bell diameter (cm)		Weight (g)		Length-weight relationship			Condition factor		Relationship
		Range (Min-max) cm	Mean±SD (cm)	Range (Min-max) (g)	Mean±SD (g)	a	b	R^2	Range (Min-max)	Mean±SD	
Cyanea nozakii	104	10.5-49	19.1±5.9	110-7400	607.4±1067.3	0.5088	2.402	0.942	0.291-1.698	1.000±0.251	Negative allometry
Chrysaora chinensis	28	4.37-11.76	8.25±2.46	14.25-68.25	43.16±17.74	1.6285	1.556	0.9187	0.810-1.280	0.982±0.146	Negative allometry
Lobonemoides robustus	27	4.5-21.5	12.95±4.28	30-560	194.17±160.96	1.0347	2.043	0.9332	0.654-1.622	1.000±0.214	Negative allometry

*SD-standard deviation

and columnar coastal waters and the benthic nature of shrimp does not interact much to affect each other but its predation effect on benthic jellyfish polyp is poorly known. However, jellyfish may have considerable influence on the pelagic resources, zooplankton, fish eggs and larvae. Thus, continuous monitoring can help understand the long-term implications of the jellyfish abundance on zooplankton, fish eggs and larvae and their influence on recruitment of commercially important fishery resources along the Tamil Nadu coastline. Further demarcating jellyfish occurring areas as 'Jellyfish Focal Areas' (JFA) for better management of commercial fishing operations in both the Gulf of Mannar and Palk Bay is put forth.

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Author contributions

Conceptualisation: MR; Methodology: MR, RS; Data Collection: MR, ST, KS; Data Analysis: MR, RS, ST; Writing Original Draft: MR; Writing Review and Editing: MR, RS, SJK; Supervision: AKA

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical Statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of samples/ protected environments.

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Diversity of meiobenthic polychaetes along the Tamil Nadu coast, India

Sasmita Swain, R. Raguna and P. Murugesan*
Centre of Advanced Study in Marine Biology, Annamalai University, Parangipettai- 608 502, Tamil Nadu, India.

*Correspondence e-mail- pmurugesaan74@gmail.com
ORCiD: https://orcid.org/0000-0002-1829-9261

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Original Article

Abstract

This study investigates the spatial and temporal variations of meiobenthic polychaete assemblages along the Tamil Nadu coast from April 2021 to November 2024. Benthic sampling at eight transects, each with near-shore and offshore stations with two replicate samples, revealed that Spionidae, especially *Prionospio polybranchiata*, dominated the community. Nearshore sites exhibited significantly higher diversity compared to offshore locations, correlating with environmental factors such as total organic carbon (TOC), sediment silt content, and dissolved oxygen. Of the total transects, Mahabalipuram stations displayed a unique community composition, characterised by the absence of Spionidae and presence of Syllidae and Sigalionidae, reflecting localised habitat heterogeneity linked to sediment characteristics and low TOC. Overall, the findings highlight the critical role of organic matter and sediment texture in shaping meiobenthic polychaete distribution and thereby emphasise the ecological significance of these taxa in coastal ecosystems. The study underscores the importance of integrated long-term monitoring to distinguish and also to ascertain the inter-annual variability from anthropogenic impacts along this dynamic coastline.

Keywords: *Meiobenthic polychaetes, Spionidae, Prionospio polybranchiata, spatial variation, temporal variation, total organic carbon*

Introduction

The study of marine meiobenthos began in the mid-1960s in the northwestern Black Sea (Vorobyova *et al*., 2008). Meiobenthos are microscopic, bottom-dwelling invertebrates, typically ranging in size from 20 to 100 μm (Majdi *et al*., 2020; 2022). They play a vital role in stimulating microbial organic matter mineralisation and nutrient cycling in sediments, which enhances nitrogen cycling and supports primary production (Aller, 1982; Ólafsson and Moore, 1990; Coull, 1999; Danovaro *et al*., 2007). Meiobenthic organisms also serve as a food source for higher trophic levels, with up to 75% of their production transferred to these levels in soft-bottom ecosystems (Brodnicke *et al.,* 2022). The meiobenthic community includes diverse taxa such as polychaetes, nematodes, copepods, and foraminiferans. Polychaetes, although traditionally considered macrobenthic, can occur in the meiobenthic fraction, especially as juvenile forms or small-bodied interstitial species (McIntyre, 1969; Kryvokhyzhyna *et al*., 2022). These organisms serve as an important transitional group between meiofaunal and macrofaunal communities, with ecological significance that warrants clarification of their size-based distinction.

Polychaetes are abundant and diverse in benthic ecosystems, with studies on meiobenthic polychaetes being limited (Shah and Mohan, 2021). These species, inhabiting interstitial spaces in sediment, are highly adaptable and possess specialised morphological features for their lifestyle (Giere, 2009). Early studies on meiobenthic polychaetes were conducted by Rao (1972) and Westheide (1977), with later studies expanding on distribution and diversity patterns (Rao and Misra, 1983; Westheide, 1991; Villora-Moreno, 1997). Research from the Chennai coast (Kesavaraj *et al*., 2024) and the Aamayizhanchan Canal (Sumesh and Abraham, 2024) highlights the role of polychaetes in ecosystem functioning and their potential as bioindicators. Similarly, studies around the Andaman–Nicobar archipelago (Gopal *et al*., 2020) emphasise their contribution to ecosystem dynamics across various habitats. Despite these findings, significant knowledge gaps remain regarding the diversity of meiobenthic polychaetes along the Tamil Nadu coast. The present study aims to explore the diversity and inter-annual variations of these polychaetes to better understand their distribution and environmental relationships.

Material and methods

Study area

The present study was conducted along the Tamil Nadu coastline. A total of eight transects perpendicular to the shoreline were fixed in the following coastal belt: Ennore, Adyar, Mahabalipuram, Puducherry, Cuddalore, Parangipettai, Karaikal, and Thoothukudi. Each transect comprised two sampling sites representing distinct hydrographic regimes: a nearshore (NS) site, located within 0.5–2 km from the coastline, and an offshore (OS) site, situated in deeper waters 3–10 km from the shoreline. Sixteen sampling stations were fixed. This sampling design was made in such a way as to consider horizontal environmental gradients, from areas strongly influenced by anthropogenic activities to relatively pristine open coastal waters (Fig. 1).

Sample collection

Sampling was conducted annually from April 2021 to December 2024 to ascertain both spatial and temporal variations in meiobenthic polychaete communities along the Tamil Nadu coast. At each site, sediment samples were collected using a Van Veen grab sampler covering an area of 0.4 m^2, then meiobenthic samples were collected with a corer covering an area of 12.5 cm^2. From each station, two replicate sediment samples were collected and stored in a zip-lock cover and brought to the shore. Sediments were sieved through a two-stage sieving system: collected sediment samples initially sieved with a 1mm mesh sieve for collecting the macrobenthos, if any, and later with a 63 μm mesh, following the standard meiobenthic extraction protocols (Holme and Macintyre, 1972). The sieve remains were preserved in 70% ethanol along with a few drops of Rose Bengal stain to facilitate easy spotting of specimens during sorting and identification. In the laboratory, sediment samples were processed carefully to maintain structural integrity and minimise sample loss. Accordingly, benthic specimens were meticulously sorted using fine tungsten needles and a brush, then assessed for morphological characters critical for taxonomic identification. The meiobenthic polychaetes obtained from sediment samples were carefully examined under a Leica DM 2500 LED compound microscope. Meiobenthic polychaetes were identified to the lowest possible taxonomic level using authoritative references and standard taxonomic keys, including Southern (1921), Fauvel (1953) and Day (1967).

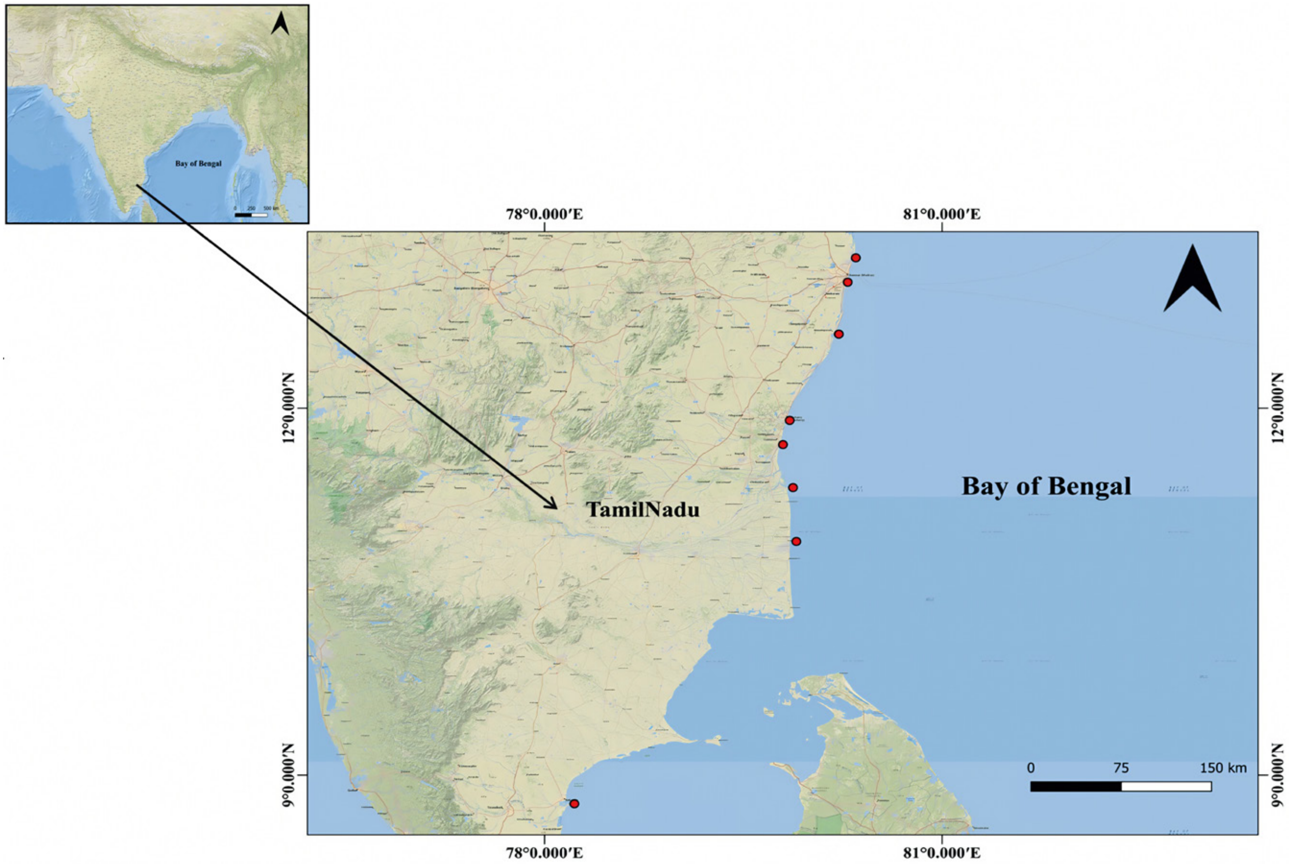

Fig. 1. Map showing sampling sites at Tamil Nadu Coastal waters

The abundance of meiobenthic polychaetes was recorded as the number of individuals per core and standardised to individuals per 1 m^2 of sediment.

Analysis of environmental parameters

In parallel, the water samples were taken from the respective stations to measure salinity (ppt), temperature (°C), pH, dissolved oxygen (DO, mg L^{-1}), sediment texture and Total Organic Carbon (TOC) analyses to characterise sediment composition and organic matter, respectively, using the Walkley–Black method (Gaudette *et al.*, 1974).

Data analysis

Quantitative analyses of meiofauna included species diversity and dominance indices. Multivariate community analyses were also performed using PRIMER v7 software. Cluster analyses and ordination techniques, including non-metric multidimensional scaling (MDS), were employed to visualise relationships spatially and temporally. SIMPER test was also computed to find out the similarity/dissimilarity in meiobenthic community composition among stations. Correlations between environmental variables and polychaete community patterns were assessed using the BIO-ENV routine, providing insight into environmental drivers of spatial and temporal variability.

Results

Environmental characteristics

Physico-chemical parameters measured in water and sediment samples across 16 stations along the Tamil Nadu coast over three years (I: 2021–2022, II: 2022–2023, III: 2023–2024) (NS: Nearshore, OS: Offshore) showed clear spatial and temporal variability. Salinity varied from 31.74 ppt at I-Thoothukudi-NS to a maximum of 34.49 ppt at I-Mahabalipuram-OS and II-Mahabalipuram-NS. Water temperature ranged between 27.07 °C at I-Ennore-NS and 30.04 °C at I- and III-Puducherry-NS. pH values remained relatively stable across all stations, ranging from 7.90 to 8.01. Dissolved oxygen (DO) exhibited a pronounced spatial gradient, with the lowest value recorded at I-Mahabalipuram-NS (2.71 mg/l) and the highest at II-Parangipettai-NS and III-Parangipettai-OS (6.53 mg/l). Sediments were predominantly sandy, with sand fractions generally exceeding 85–95%, particularly at nearshore stations such as Mahabalipuram and Puducherry, ranging from 99.42% at I-Puducherry-NS to 2.37% at III-Parangipettai-OS. Silt content showed wide variation, from 0.28% at I-Puducherry-NS to 89.81% at III-Parangipettai-OS, while clay fractions remained consistently low (0.30–7.72%). Total organic carbon (TOC) concentrations ranged from 2.22 mgC/g at I-Puducherry-OS to a maximum of 18.41 mgC/g at II–III-Parangipettai-NS during the study period.

Community structure

A total of 19 species of meio-benthic polychaete species were recorded throughout the study period (2021–2024) from the selected stations along the Tamil Nadu coast. Among the species collected, members of Spionidae were found to be dominant with 6 species, followed by Sigalionidae with 5 species, Syllidae and Cossuridae came next in the order with 2 species each and lastly Cirratulidae, Capitellidae, Melinnidae and Phyllodocidae with 1 species each. Among the stations, the maximum species (6) was found in Adyar and Parangipettai (Near shore station) in 2022-23, Karaikal (Near shore) in 2023-24, and the minimum (2) was at mostly offshore stations. Looking at the species composition, *Prinospio polybranchiata, Paraprionospio lamellibranchia* (juvenile) were the dominant species found in almost all the stations except Mahabalipuram. Overall, the density varied from

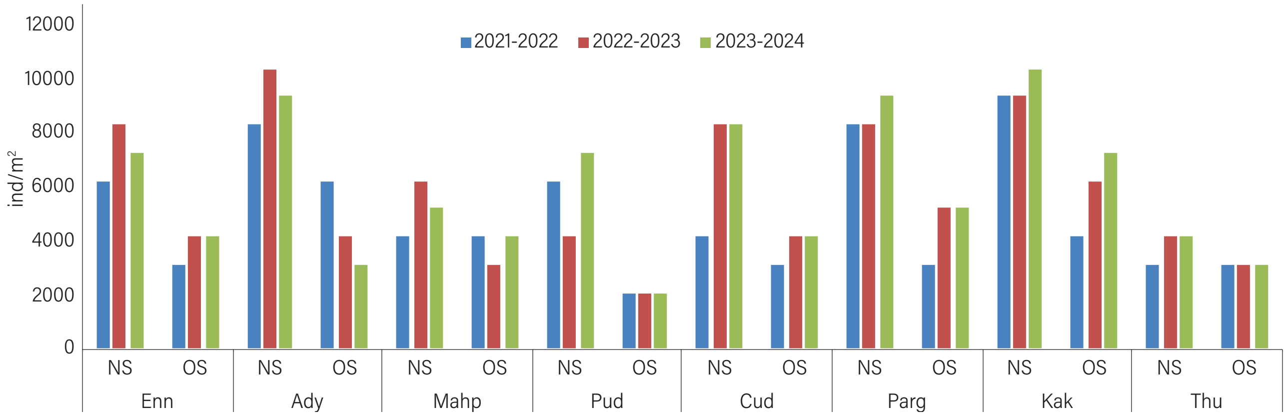

Fig. 2. Density of meiobenthic polychaetes recorded at different sampling stations during the study period. Sampling stations categorised as nearshore (NS) and offshore (OS), including Ennore (Enn), Adyar (Ady), Mahabalipuram (Mahp), Puducherry (Pud), Cuddalore (Cud), Parangipettai (Parg), Karaikal (Kak), and Thoothukudi (Thu)

2083 ind/m^2 at Puducherry (Offshore) for all three years to 10,417 ind/m^2 during 2022-23 (Adyar- Near shore), and 2023-24 (Karaikal- Near shore).

Over the years, the density varied from 79,167 ind/m^2 in 2021-22 to 94,793 ind/m^2 in 2023-24. Spatially, in near-shore stations, the minimum density (3125 ind/m^2) was recorded in Thuthukudi during 2021-22 and the maximum (10,417 ind/m^2) in Adyar during 2022-23 and in Karaikal during 2023-24. Similarly, when the values were looked at offshore stations, a minimum density of 2083 ind/m^2 was recorded in Puducherry during 2021-24, and a maximum of 7291 ind/m^2 was in Karaikal during 2023-24 (Fig. 2).

Diversity indices (Table 1) revealed a clear spatial and temporal variation. The Shannon- diversity index varied from 0.56 to 1.7 with minimum was in Ennore (off shore) and Cuddalore (off shore) during 2022-23 and maximum was in Parangipettai (Nearshore) during 2022-23 was in Parangipettai (Nearshore) during 2022-23; Margalef's species richness ranged from a minimum of 0.12, recorded in offshore samples from Mahabalipuram and Karaikal during 2021–22, Ennore and Cuddalore offshore during 2022–23, and Ennore offshore during 2023–24, to a maximum of 0.55 at the Parangipettai nearshore station during 2022–23; Pielou's evenness ranged from 0.81 to 1 with minimum at Off shore regions in Ennore and Cuddalore during 2022-23 and in Ennore during 2023-24; Simpson dominance index was found to vary from 0.37 to 0.81 with minimum in the samples collected Off shore regions of Ennore and Cuddalore in 2022-23 and in Ennore during 2023-24 and maximum at Paranipettai (Nearshore) during 2022-23 (Table 1).

The SIMPER analysis revealed that average within-group similarity was 29.33%, 34.81%, 33.42% for I, II and III

Table 1. Diversity indices of meiobenthic polychaetes recorded from coastal waters of Tamil Nadu during 2021–2024, including total number of species, total number of individuals, Shannon–Wiener diversity (H'), Margalef species richness (d), Pielou's evenness (J'), and Simpson's dominance (D). Sampling stations categorised as nearshore (NS) and offshore (OS), including Ennore (Enn), Adyar (Ady), Mahabalipuram (Mahp), Puducherry (Pud), Cuddalore (Cud), Parangipettai (Parg), Karaikal (Kak), and Thoothukudi (Thu)

Period	Sample	Total Species	Total Individuals	Margalef richness (d)	Pielou's evenness (J')	Shannon Diversity H'(log2)	Simpson Dominance (D)
2021-2022	Enn-NS	3	6250	0.23	0.92	1.01	0.61
	Enn-OS	3	3125	0.25	1	1.09	0.67
	Ady-NS	4	8333	0.33	0.87	1.21	0.66
	Ady-OS	3	6250	0.23	0.92	1.01	0.61
	Mahp-NS	3	4167	0.24	0.95	1.04	0.62
	Mahp-OS	2	4167	0.12	1	0.69	0.51
	Pud-NS	3	6250	0.23	0.92	1.01	0.61
	Pud-OS	2	2083	0.13	1	0.69	0.52
	Cud-NS	3	4167	0.24	0.95	1.04	0.62
	Cud-OS	3	3125	0.25	1	1.09	0.67
	Parg-NS	4	8333	0.33	0.95	1.32	0.72
	Parg-OS	2	3125	0.13	0.92	0.64	0.44
	Kak-NS	4	9375	0.33	0.88	1.21	0.67
	Kak-OS	2	4167	0.12	1	0.69	0.51
	Thu-NS	3	6250	0.23	0.92	1.01	0.61
	Thu-OS	3	3125	0.25	1	1.09	0.67
2022-2023	Enn-NS	5	8333	0.44	0.93	1.49	0.75
	Enn-OS	2	4167	0.12	0.81	0.56	0.37
	Ady-NS	6	10417	0.54	0.95	1.69	0.81
	Ady-OS	3	4167	0.24	0.95	1.04	0.62
	Mahp-NS	4	6250	0.34	0.96	1.33	0.72
	Mahp-OS	2	3125	0.13	0.91	0.64	0.44
	Pud-NS	3	4167	0.24	0.95	1.04	0.62
	Pud-OS	2	2083	0.13	1	0.69	0.52
	Cud-NS	4	8333	0.33	0.95	1.32	0.72
	Cud-OS	2	4167	0.12	0.81	0.56	0.37
	Parg-NS	6	8333	0.55	0.97	1.73	0.81
	Parg-OS	4	5208	0.35	0.96	1.33	0.72
	Kak-NS	4	9375	0.33	0.88	1.21	0.67
	Kak-OS	4	6250	0.34	0.96	1.33	0.72
	Thu-NS	3	4167	0.24	0.95	1.04	0.62
	Thu-OS	2	3125	0.13	0.92	0.64	0.44

Period	Sample	Total Species	Total Individuals	Margalef richness (d)	Pielou's evenness (J')	Shannon Diversity H'(log2)	Simpson Dominance (D)
2023-2024	Enn-NS	5	7292	0.45	0.96	1.55	0.77
	Enn-OS	2	4167	0.12	0.81	0.56	0.37
	Ady-NS	4	9375	0.33	0.94	1.31	0.71
	Ady-OS	2	3125	0.13	0.92	0.64	0.44
	Mahp-NS	3	5208	0.23	0.86	0.95	0.56
	Mahp-OS	3	4167	0.24	0.95	1.04	0.62
	Pud-NS	4	7292	0.34	0.92	1.28	0.69
	Pud-OS	2	2083	0.13	1	0.69	0.52
	Cud-NS	5	8333	0.44	0.93	1.49	0.75
	Cud-OS	3	4167	0.24	0.95	1.04	0.62
	Parg-NS	5	9375	0.44	0.95	1.52	0.76
	Parg-OS	3	5208	0.23	0.86	0.95	0.56
	Kak-NS	6	10417	0.54	0.95	1.70	0.8
	Kak-OS	5	7292	0.45	0.92	1.47	0.73
	Thu-NS	3	4167	0.24	0.95	1.04	0.62
	Thu-OS	2	3125	0.13	0.92	0.64	0.44

years, respectively. Across the years, the assemblage was overwhelmingly formed by a single dominant species, *Prinospio polybranchiata*, which contributed the largest proportion of within-group similarity as 66.98%, 72.24% and 72.90% respectively in I, II & III years. Two other species *Paraprionospio lamellibranchi* (juvenile) and *Capitella singularis* (juvenile), were the next most important contributors, typically > 85% similarity during the study period. In 1st Year (2021–2022), the average similarity was 29.33% with contributors *P. polybranchiata* with 66.98%, *P. lamellibranchia* (juvenile) with 18.34% and *C. singularis* (juveniles) with 10.33%. During II Year (2022–2023), average similarity was 34.81%; *P. polybranchiata* remained dominant by contributing 72.24%, and with moderate contributions from *P. lamellibranchia* (juvenile) (8.12%), *C. singularis* juveniles (4.37%) and *Parapionosyllis subterranea* (4.25%). During the 3rd year (2023–2024), the average similarity was 33.42%; *P. polybranchiata* continued to contribute more with 72.90%, followed by *P. lamellibranchia* (juvenile) with 8.13% and *Polydora hornelli* with 4.17%, as these were the principal similarity drivers; *Sphaerosyllis minima* also contributed within the top five taxa (cumulative ~90.9%).

The average dissimilarity during I and II; I and III, and II and III years was 67.20%, 65.56% and 64.50%, respectively. The taxa most responsible for inter-year dissimilarity were consistently *P. lamellibranchia* (juvenile), *Prinospio polybranchiata* and *C. singularis* juveniles, supplemented by species such as *P. subterranea*, *Cossura* spp., *Ctenodrilus serratus*, *Polydora hornelli* and *Sphaerosyllis minima* depending on the pairwise comparison.

Average within-group similarity for nearshore (NS) and offshore (OS) samples was 33.45% and 31.59%, respectively. Nearshore samples showed greater taxonomic heterogeneity than offshore samples. NS assemblages were dominated by *P. polybranchiata* (Average. Similarity- 19.21), contributing 57.43%, followed by *P. lamellibranchia* (juvenile) with 15.86% and *Capitella singularis* juveniles with 8.68%. Several secondary taxa, namely *Parapionosyllis subterranea*, *Prionospio krusadensis*, *Pseudopolydora kempi*, also contributed cumulatively to nearshore similarity, reflecting higher diversity. With regard to OS, faunal assemblages were highly dominated by *Prinospio polybranchiata*, which alone accounted for 85.13% of within-group similarity, and a few other taxa contributed meaningfully. The average dissimilarity between NS and OS groups was 67.34%, with top contributors between these two being *P. lamellibranchia* (12.64%), *Capitella singularis* juveniles (9.95%) and *P. polybranchiata* (9.86%) followed by *Parapionosyllis subterranea*, *Cossura* spp., and *Sphaerosyllis minima* with a meagre.

The Bray–Curtis similarity (fourth-root transformed) clustering (Fig. 3) and corresponding non-metric multidimensional scaling (nMDS) (Fig. 4) jointly depicted a coherent pattern of moderate overlapping of years and shore types. Most of the NS and OS stations got clustered together from all three years, demonstrating overall structural stability in community composition. Interestingly, both nearshore and offshore stations of Mahabalipuram during all three years and that of Karaikal and Thoothukudi only in I year were found apart from the main clustering pattern, which might be due to the absence of spionidae.

The BIOENV (BEST) analysis was performed to identify the combination of environmental variables that best explains the variation observed in the biotic similarity matrix using Spearman's rank correlation. The environmental dataset

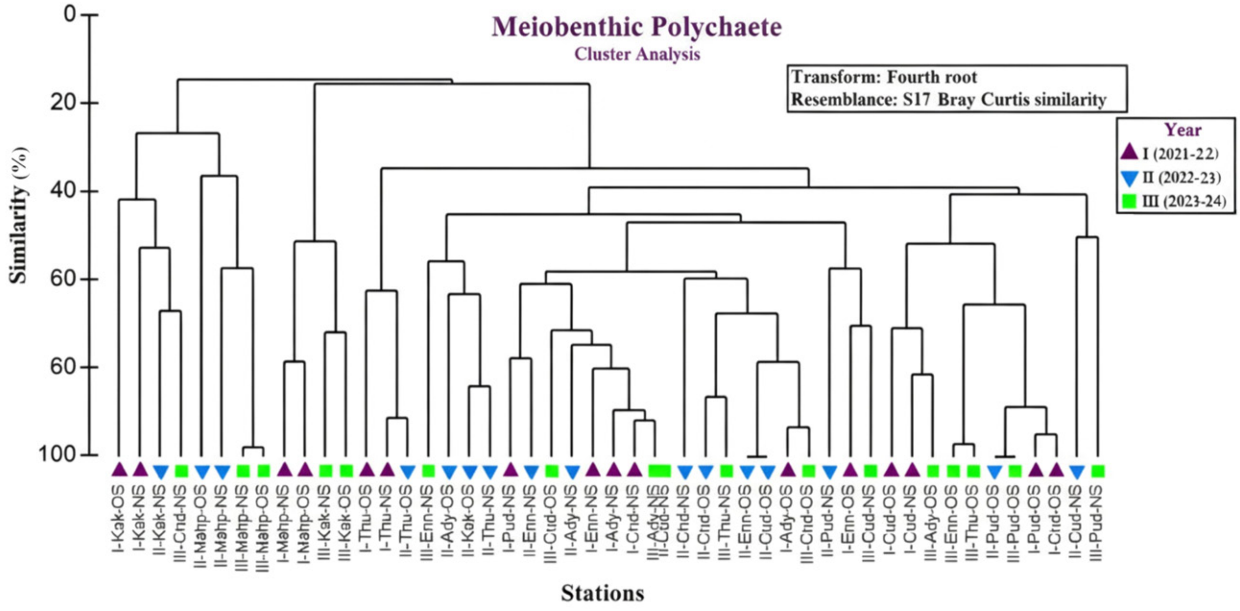

Fig. 3. Cluster analysis of meiobenthic polychaete abundance data collected over three years (2021–2024) from the coastal waters of Tamil Nadu. Sampling stations were categorised as nearshore (NS) and offshore (OS), including Ennore (Enn), Adyar (Ady), Mahabalipuram (Mahp), Puducherry (Pud), Cuddalore (Cud), Parangipettai (Parg), Karaikal (Kak), and Thoothukudi (Thu)

included nine variables: total organic carbon (TOC), total organic matter (TOM), sand, silt, clay, dissolved oxygen (DO), temperature, salinity, and pH. The resemblance among environmental samples was based on Euclidean distance. The BIOENV results revealed that, among the variables, TOC alone emerged as a single parameter showing the highest correlation (ρ = 0.731) with the biotic pattern. When combined variables were tested, Silt and TOC emerged as the best two-variable match with a correlation of ρ = 0.652. The top three-variable combination (TOC, silt, and DO) produced a correlation of ρ = 0.649. Further combinations of more than three variables did not significantly improve the correlation, indicating that TOC, either alone or in association with silt and DO, was the most influential environmental factor structuring the distribution of meiobenthic organisms biota (Table 2).

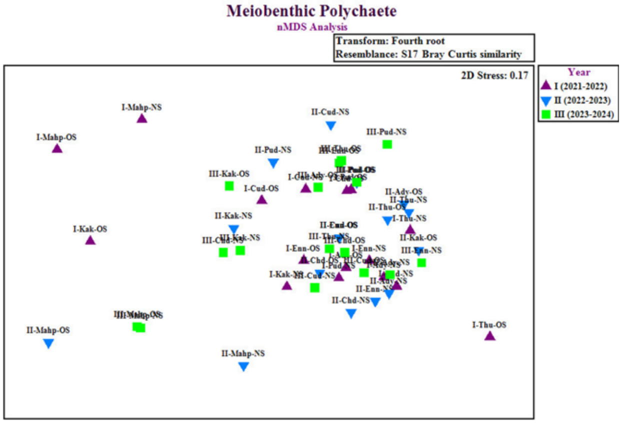

Fig. 4. Non-metric multidimensional scaling (nMDS) ordination of meiobenthic polychaete abundance data collected over three years (2021–2024) from coastal waters of Tamil Nadu. Sampling stations were categorised as nearshore (NS) and offshore (OS), including Ennore (Enn), Adyar (Ady), Mahabalipuram (Mahp), Puducherry (Pud), Cuddalore (Cud), Parangipettai (Parg), Karaikal (Kak), and Thoothukudi (Thu)

Table 2. Spearman rank correlation (pω) between meiobenthic polychaete abundance and environmental similarity matrices in various stations of Tamil Nadu coastal waters during 2021-2024. Environmental variables categorized as Total organic carbon (TOC*), Dissolve Oxygen (DO*), Temperature (Temp.*)

Variables	Correlati (pω)
TOC	0.731
Silt, TOC	0.652
TOC, Silt, DO	0.649
TOC, DO	0.633
Silt, TOC, Temp.	0.629
TOC, Silt, DO, Temp.	0.628

Discussion

The present study reveals clear spatial and temporal variation in meiobenthic polychaete assemblages along the Tamil Nadu coast, with distinct dominance patterns and environmental structuring across stations and years. Among the polychaete families recorded, Spionidae emerged as the most speciose and abundant group, consistent with their known adaptability to a wide range of sedimentary and organic conditions as stated by Blake (1996) and Taghon *et al.* (1980). Their dominance, particularly of *P. polybranchiata*, across all the years and stations underscores the opportunistic and eurytopic nature of this taxon in organically enriched and fine-grained sediments. In their study, Vorobyova *et al.* (2008), on meiobenthic polychaetes in the northwestern Black Sea, reported similar dominance of spionids in shallow coastal environments, suggesting this family's prevalence in meiofaunal size classes may be a widespread phenomenon in productive coastal ecosystems globally. Notably, macrobenthic studies done during yesteryears from the Tamil Nadu coast have also documented overwhelming spionid dominance in adult polychaete assemblages (Joydas and Damodaran, 2009; Murugesan *et al*., 2018; Sivadas and Carvalho, 2020), with species such as *Prionospio* spp., *Polydora* spp., and *Paraprionospio* spp. consistently ranking among the most abundant taxa in shallow coastal sediments. The congruence between our meiofaunal findings and these macrobenthic patterns strongly suggests that the juvenile spionids documented in our study represent recruitment stages of the dominant macrofaunal populations, creating a vertically integrated community structure where spionids dominate across both size classes. This ontogenetic continuity with juveniles in the meiofaunal fraction transitioning to adults in the macrofaunal assemblage underscores the ecological and numerical importance of Spionidae throughout their life cycle in Bay of Bengal coastal ecosystems.

A total of 19 meiobenthic polychaete species recorded in the present study is comparable to the findings of Vorobyova *et al.* (2008), who reported 20 species in a similar kind of investigation in Black Sea. This similarity may be attributed to the fact that polychaetes constitute a relatively small component of the meiobenthic community compared to other meiofaunal groups. In the Indian context, across estuaries, canals, and nearshore shelf, meiobenthic polychaetes are reported to form ~3–11% of individuals, most often at the lower end (2–7%), with foraminifera or nematodes strongly dominating the taxa (Sumesh and Abraham, 2024). These observations collectively suggest that relatively low species richness of meiobenthic polychaetes is a common pattern one can see across different coastal systems, reflecting their subordinate contribution to overall meiobenthic diversity.

Univariate diversity indices indicated generally low to moderate species richness and diversity (Table 1), reflecting the smaller group of polychaete in the meiobenthic group, as polychaetes are mainly temporary meiobenthos (Ansari *et al*., 2012). The higher species diversity and richness at nearshore sites, particularly Parangipettai Nearshore suggests according to this study, this particulatr stations' habitats have offered favourable conditions, such as enhanced organic availability and sediment stability. Along the Aamayizhanchan Canal of Thiruvananthapuram City, Kerala, Sumesh and Abraham (2024) demonstrated similar dominance of meiobenthic polychaetes where organic matter and finer sediments were prevalent, with distributions strongly responding to organic carbon (C org), total organic matter (TOM), and carbohydrate content. Similarly, maximum evenness recorded at several offshore stations indicates relatively balanced species abundances where multiple taxa co-occurred, while low values at nearshore reflecting strong dominance (Table 1).

The density pattern further supports these observations, with nearshore stations exhibiting higher polychaete densities compared to offshore stations. The elevated densities recorded in nearshore habitats are plausibly associated with higher organic matter deposition and the prevalence of finer sediments, which providing conducive environment for detritivorous and tubicolous polychaete taxa such as *Prionospio* and *Paraprionospio* spp. The strong temporal stability in assemblage composition, as shown by similar within-year similarities (~30–35%) and repeated dominance by the same few species, suggests resilience of these opportunistic taxa under fluctuating coastal conditions. However, the observed interannual dissimilarities (64–67%) indicate subtle shifts in community composition, likely driven by episodic changes in sediment texture and organic matter input associated with monsoonal cycles, as well as localised anthropogenic disturbances such as sewage and industrial discharges and increased boating activity.

Spatially, nearshore (NS) assemblages exhibited greater taxonomic heterogeneity than offshore (OS), despite both being dominated by *Prionospio polybranchiata*. The contribution of secondary taxa such as *Paraprionospio lamellibranchia, Capitella singularis*, *Parapionosyllis subterranea*, and *Pseudopolydora kempi* at NS sites reflects microhabitat diversity and varying organic enrichment levels. The clustering (Fig. 3) and nMDS (Fig. 4) ordination revealed an overall structural stability in community composition, but the consistent outlier pattern of Mahabalipuram samples might be due to the replacement of Spionid polychaetes with Syllidae and Sigalionidae, indicating localised habitat heterogeneity.

The BIOENV analysis identified total organic carbon (TOC) as the single most influential environmental variable shaping meiobenthic polychaete assemblages, with the best correlations achieved when TOC was combined with silt and dissolved oxygen (Table 2). This finding corroborates the earlier studies emphasising the role of organic enrichment in structuring small-sized benthic fauna (Coull, 1999; Giere, 2009). The positive association between TOC and polychaete abundance indicates that moderate enrichment enhances food availability for deposit feeders.

The consistent absence of Spionidae at both nearshore and offshore stations of Mahabalipuram across all three years represents a marked deviation from the general assemblage structure along the Tamil Nadu coast. Spionid polychaetes, particularly *Prionospio* and *Paraprionospio,* are typically associated with fine-grained, organically enriched sediments that favour tube-building and deposit-feeding strategies (To-Orn *et al*., 2015; Johnson *et al*., 2025). Their absence at Mahabalipuram suggests locally unsuitable sedimentary conditions, such as coarser substrates, lower organic matter availability, or increased sediment mobility, which may limit tube stability and feeding efficiency. In contrast, the dominance of Syllidae and Sigalionidae indicates a shift toward more mobile or predatory taxa adapted to heterogeneous or physically disturbed habitats. Similar taxonomic replacements under low organic enrichment or altered sediment conditions have been reported elsewhere, underscoring the role of fine-scale habitat heterogeneity in structuring meiobenthic polychaete assemblages. Targeted, site-specific studies are required to elucidate the precise environmental drivers underlying the distinctive meiobenthic assemblage structure observed at Mahabalipuram.

Added to this, Spionid polychaetes are widely recognised as effective bioindicators of organic enrichment, eutrophication, and certain forms of pollution in soft-sediment environments, particularly when assessed at the community level rather than through total abundance alone. Reviews of Latin American and Caribbean studies identify Spionidae as a key indicator family, with genera such as *Scolelepis*, *Spiophanes*, *Streblospio*, *Polydora*, and *Prionospio* frequently used in assessments of sediment disturbance and organic loading (Elías *et al*., 2020). However, species-specific responses within the family are well documented, with some spionids exhibiting high tolerance to organically enriched or reducing sediments, while others are more sensitive to environmental stressors (Agustina *et al*., 2018). Consequently, recent studies emphasise the use of spionids within multimetric or trait-based frameworks rather than as binary indicators of disturbance (Elías *et al*., 2020; Maximov and Berezina, 2023). In the present study, the dominance of spionid taxa across most stations, coupled with clear spatial differentiation in community composition revealed by nMDS, supports the interpretation that organic matter availability and sediment characteristics jointly structure meiobenthic assemblages, rather than spionid presence alone serving as a simple indicator of disturbance.

The observed spatial variability in meiobenthic polychaete assemblages highlights the sensitivity of these organisms to subtle changes in sedimentary and organic matter conditions. Many juvenile polychaetes pass through a short-lived meiobenthic phase that is closely linked to reproductive timing and bottom-water temperature, resulting in rapid shifts in local α-diversity under changing environmental conditions in black sea (Bondarenko and Vorobyova, 2023). Similarly, in the Matla River of Sundarbans estuary, meiobenthic communities are characterised by small body size, high abundance, short generation times, and limited mobility, making them particularly responsive to fine-scale variations in sediment characteristics and organic matter availability (Ghosh and Mandal, 2021). Earlier studies indicate that small, worm-shaped or actively swimming meiobenthic taxa respond rapidly to changes in substrate stability and organic enrichment, with community structure shifting under altered sediment and food conditions (Kryvokhyzhyna *et al*., 2022). Polychaetes are, therefore, widely recognized as effective bioindicators of environmental quality and anthropogenic disturbance across diverse marine regions (Elías *et al*., 2020), and functional trait-based approaches demonstrate that traits such as body size, mobility, and feeding mode reliably reflect gradients in organic matter, sediment composition, and habitat complexity (Charrier *et al*., 2022; Miri *et al*., 2023).

Overall, the present study highlights that meiobenthic polychaete assemblages along the Tamil Nadu coast are strongly influenced by organic enrichment and sediment characteristics. The recurrent dominance of Spionid polychaetes, particularly *Prionospio polybranchiata*, coupled with maximum diversity at nearshore stations, reflects a community typical of organically influenced coastal systems. However, continued monitoring, integrating environmental and biological indicators, is essential to assess long-term ecological changes and also to distinguish natural variability from anthropogenic impacts along this dynamic coastline.

Conclusion

The study concludes that meiobenthic polychaete assemblages along the Tamil Nadu coast exhibit clear spatial and temporal variations, with Spionidae, particularly *Prionospio polybranchiata*, dominating the community. Nearshore stations harboured significantly higher density and diversity compared to offshore sites, reflecting more favourable environmental conditions such as organic enrichment and sediment stability for the recoupment of meiobenthic polychaetes. The assemblage structure shows resilience over time but also subtle inter-annual shifts likely influenced by environmental fluctuations. Total organic carbon (TOC), along with silt and dissolved oxygen, emerged as the key environmental factors shaping these meiobenthic polychaetes. The absence of Spionidae and the appearance of other families like Syllidae and Sigalionidae at Mahabalipuram highlight localised habitat heterogeneity driven by sediment characteristics. The findings underscore the strong influence of organic matter and sediment texture on meiobenthic polychaete distribution, emphasising the ecological importance of these taxa in coastal ecosystems and the need for integrated long-term monitoring to discern natural variability from anthropogenic impacts.

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Author contributions

Conceptualisation: SS, PM; Methodology: SS, RR, PM; Data Collection: SS; Data Analysis: SS, RR; Writing Original Draft: SS, RR; Writing Review and Editing: PM; Supervision: PM

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required, as the study does not involve activities that necessitate ethical approval or involve protected organisms/human subjects, or the collection of samples from protected environments.

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Regulating ecotourism is the key to protecting intertidal ecology along the Magna coast, Saudi Arabia

G. Nandhagopal[1,2]*, Thamer Al-Johani[1], Rawan Saad W. Aljohani[1] and Kevin Patrick Kelly[1,2]
[1]Environmental Protection and Control Department, Royal Commission for Jubail and Yanbu, Jazan City for Primary and Downstream Industries, Saudi Arabia.
[2]PARSONS, Jazan, Saudi Arabia.

*Correspondence e-mail: nandhagopal.ganesan@parsons.com
ORCiD: https://orcid.org/0000-0002-3076-1965

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Original Article

Abstract

Tourism and recreational activities pose a significant threat to intertidal ecosystems, which are more vulnerable than other marine ecosystems due to their accessibility. The Red Sea, a unique biodiversity hotspot with numerous endemic marine organisms, is under threat from the rapid development of the tourism industry in the Kingdom of Saudi Arabia (KSA). As part of an effort to protect intertidal biodiversity and enhance ecotourism, a study was conducted to identify the impact of tourism on intertidal biodiversity at a popular tourist destination along the coast of Magna, Saudi Arabia. The study identified a total of 24 species, including macroalgae (5), gastropods (7), chitons (2), sea cucumbers (2), corals (2), brittle stars (2), crab (1), bivalve (1), sea urchin (1), and fish (1). While major recreational activities are currently limited to swimming, rock pooling, fishing, and intertidal walking, they may rise in the near future through developments. The number of casualties of marine life doubled on weekends due to the high visitor count. To address this issue, the Kingdom of Saudi Arabia implemented several Royal decrees. The local government should be strict with these decrees as well as create an awareness program to educate locals and tourists about marine sustainability, particularly in the diverse rocky intertidal regions.

Keywords: *Ecotourism, recreational activities, intertidal ecosystem, Red Sea, endemic*

Introduction

The intertidal zone is the space between the high and low tide, a critical ecosystem constantly facing a series of threats through natural and anthropogenic interventions (Micheli *et al.*, 2016). In general, intertidal biodiversity flourishes with various marine organisms but is greatly influenced by physical factors such as waves, tides, and temperature (Gaylord, 1999; Calcagno *et al.*, 2012). In recent trends, the intertidal communities are facing serious threats due to the development of the coast for tourism and recreational activities (Crowe *et al.*, 2000; Davenport and Davenport, 2006). The tourism industry has grown exponentially in the last few decades, with coastal cities being the main attractions for various recreational resources (Miller, 1993; Dadon, 2002; Davenport and Davenport, 2006). Though tourism and recreational activities provide economic benefits to the countries, they still create disturbances and damage the intertidal ecosystem (Dadon, 2002; Davenport and Davenport, 2006). The impacts on the ecosystem will be in highly protected or reserved areas (Fletcher and Frid, 1997). Further, the prolonged activities will lead to the deterioration of the natural ecosystem (Mendez *et al.*, 2017). In recent decades, ecotourism has emerged as a prominent strategy for many countries to balance biodiversity conservation with tourism development (Brett, 2018; Holland *et al.*, 2022). However, the impacts of ecotourism on protected and diverse regions are multifaceted and require careful consideration of potential economic, social, and environmental trade-offs (Teshome and Demissie, 2018).

Compared to other intertidal ecosystems, the rocky intertidal ecosystem is more diverse and richer in flora and fauna. The crevices and rock pools among the rocky shoreline protect the marine organisms from predators and heat stress, which in turn leads to the flourishing of marine organisms (Nandhagopal *et al.*, 2020). These marine resources are facing serious threats due to human interventions and exploitation

(Brosnan and Crumrine, 1994; Povey and Keough, 1991; Eckrich and Holmquist, 2000; Jenkins *et al.*, 2020).

The Kingdom of Saudi Arabia is rapidly emerging as a prominent destination for tourism, boasting an extensive rocky shoreline along the Red Sea. In recent years, Saudi Arabia has launched numerous projects to attract tourists, particularly focused on the Red Sea development initiatives, such as NEOM (Ibrahim *et al.*, 2021), a flagship project of Saudi Arabia's Vision 2030. However, this fast-paced development poses serious risks to ecosystems, especially intertidal ecosystems, due to developments targeting the coastline. Nevertheless, NEOM is committed to preserving 95% of the land and sea for nature, allowing residents, wildlife, and tourists to benefit from a sustainable model of regreening and rewilding (Alam *et al.*, 2021). This initiative is one of the first and most significant globally in support of Biodiversity Sustainability. Numerous studies have shown that ecotourism is one of the effective ways to boost tourism as well as to conserve biodiversity (Abuhay *et al.*, 2023). The Red Sea is a global hotspot rich in various marine endemic organisms (DiBattista *et al.*, 2016). The region's isolation by the Gulf of Aden and the Bab al-Mandab Strait, combined with its shallow depth, high temperature, and salinity, has likely restricted the movement of marine flora and fauna (Kemp, 2000), resulting in a unique endemism. To mitigate the serious impacts of tourism development on marine ecosystems and to establish sustainable management practices, extensive research is required, particularly concerning intertidal communities. Currently, the Royal Commission of Jubail and Yanbu is developing an Environmental Sustainability City (JCPDI) in the Jazan Province along the Red Sea, incorporating the objectives of Vision 2030. This sustainable city has the potential to set a benchmark for sustainable urban development across the Kingdom of Saudi Arabia, especially in greenery and biodiversity. In general, the noninvolvement of the locals was the major reason for the failure of ecotourism policies (Liu *et al.*, 2012; Abdurahman *et al.*, 2016). Hence, the Royal Commission of Jubail and Yanbu incorporated the sustainability practices during the development stage itself by obtaining the LEED (Leadership in Energy and Environmental Design) platinum certificate for the design. As part of its efforts to support the country's ecotourism vision and identify gaps in existing policies, a first-time study was conducted on the intertidal zone along the Magna coast in Tabuk. The Magna coast is rich in flora and fauna with diverse species. This diverse ecosystem will be affected due to the rapid development of tourism industries. Hence, the current study investigated the impact of recreational activities on the diversity of rocky intertidal ecology in the selected location along the Magna Coast, Saudi Arabia.

Material and methods

Study area

Magna is a town in the Tabuk Province of Saudi Arabia. It is situated on the coast of the Gulf of Aqaba, at coordinates 28° 23′ 51″ N and 34° 44′ 59″ E, southwest of Al-Bad′ (Fig.1). The Red Sea near Magna is home to pristine coral reefs and is well-known as a scuba diving site. As a part of the NEOM project, Saudi Arabia has recently revealed plans to develop the Magna coast as one of the prime luxury lifestyle coastal destinations.

Field study

The field survey was conducted at one of the tourist spots along the Magna coast (28.399169° N, 34.738769° E) during the period of April 2024. The visitors count and activities were tracked continuously for a period of one month (April, 2024) during one weekday (Tuesday, low activity) and one weekend (Friday, peak activity) (Machado *et al.*, 2017). In Saudi Arabia, Friday and Saturday are considered weekends with high activity during Friday, which was the reason to consider Friday for the peak activity. The data was collected between 5 pm and 10 pm on both days due to peak activity time. The time period and survey day were finalised based on the preliminary survey. During the preliminary survey, continuous monitoring was carried out for a week to observe peak activity hours and days. Hence, based on the preliminary survey, the day and time were identified to obtain highly efficient data in a short period of time.

An extensive field survey was conducted along the 5 km coastal stretch of Magna to study the distribution and diversity of intertidal species. The intertidal diversity assessment was conducted in parallel with the visitor count. A series of field surveys, conducted through intertidal walking at low tide (Jebakumar *et al.*, 2015), along the entire stretch without creating any harm to the animals and the study area is presented in Fig. 1. The diversity of the intertidal samples was analysed using 1 X 1 m quadrates (Megina *et al.*, 2013). The samples were collected and coded for identification in the laboratory. They were brought in clean sample containers (one sample per container), and the specimens were photographed immediately after transportation and onsite. The sample size, shape, colour, texture, total length, breadth, and oscule diameter were noted to identify the specimen using morphological characteristics. Further, to determine the specimen's species level, individual samples were preserved in 90% alcohol (Vinod *et al.*, 2014).

The cluster analysis based on the Bray-Curtis similarity matrices of root-transformed visitor counts between the weeks was

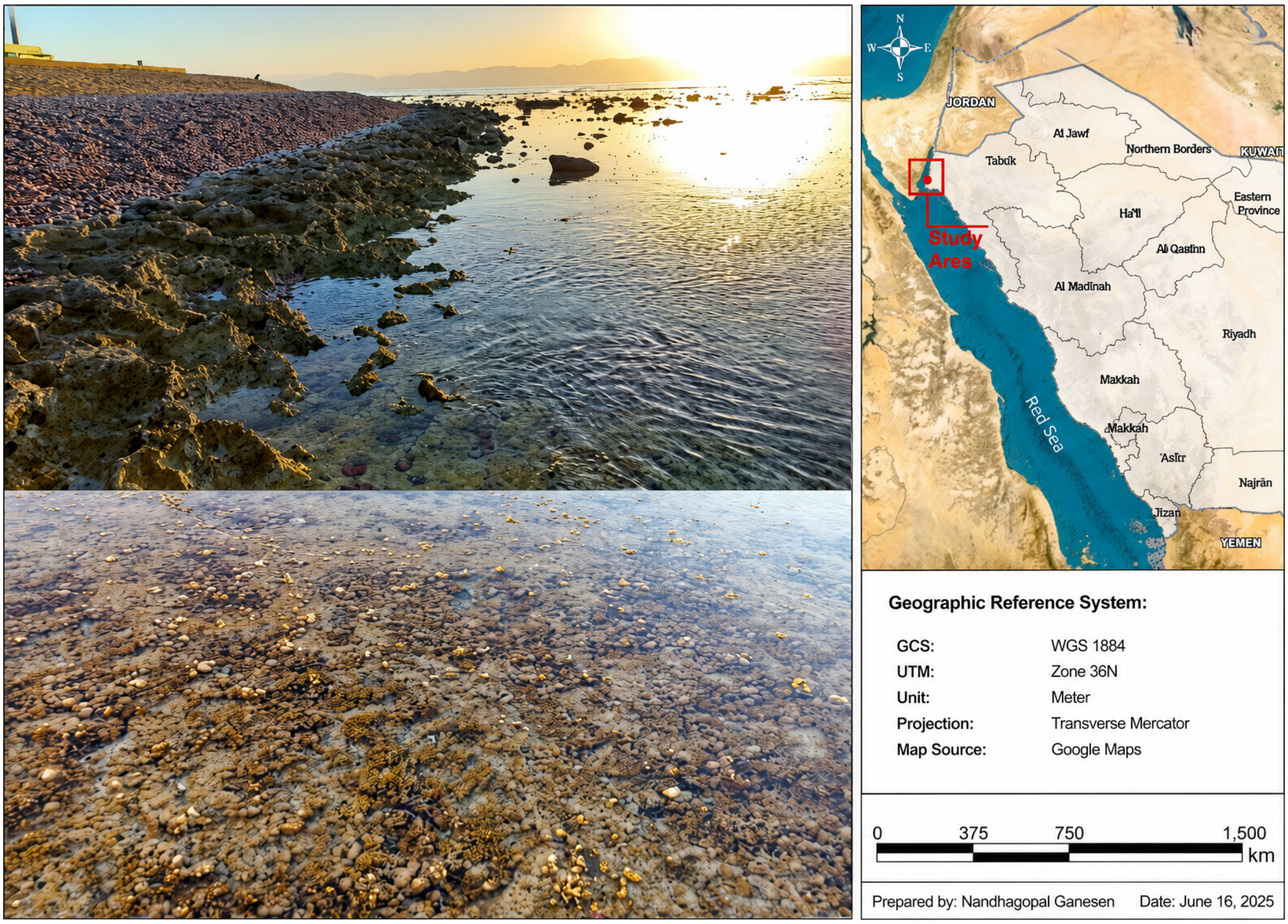

Fig. 1. Figure represents the study area

used to analyse the differences in the visitor counts between the weeks. In addition, the root-transformed visitor activities data were used to create the Non-metric multidimensional scaling ordinations (nMDS) plot based on Bray-Curtis similarity matrices. The Primer v7 was utilised to perform this analysis (Jebakumar *et al*., 2015; Nandhagopal *et al*., 2020).

Results

Visitor numbers and activities

Based on the collected data, the weekly average visitor count was significantly higher on weekends (310 visitors/hour) compared to weekdays (125 visitors/hour). The overall monthly average was 87 visitors/hour, though this likely fluctuates with seasonal cycles typical of the Red Sea. As illustrated in Fig. 2, visitor counts varied between weeks, with similarity indices shown in Fig. 3, Fig. 4 further clarifies the hourly variations in visitor counts between weekdays and weekends. Following the complete development of the NEOM coast, visitor counts could potentially increase to approximately 1000/hour, a projection that necessitates robust management interventions, such as designated walkways, to prevent the 39% increase in mechanical damage typically observed with unregulated foot traffic (Pinn and Rodgers, 2005).

Regarding activities, rock pooling and intertidal walking were the most common. Fig. 5 presents the variations in these activities between the weeks. Visitors were frequently observed walking over algae and harvesting limpets and gastropods. Adult visitors were noted to cause more significant

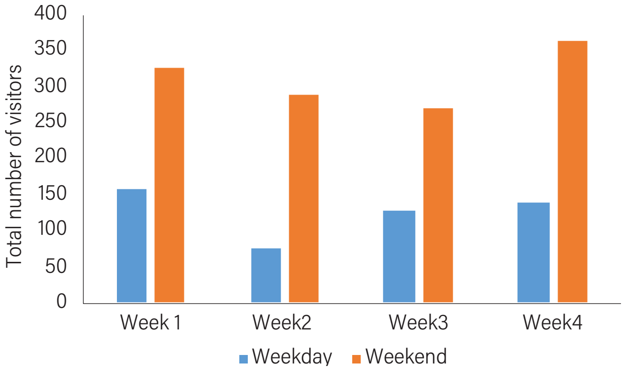

Fig. 2. Variations in the visitor count between weekdays and weekends

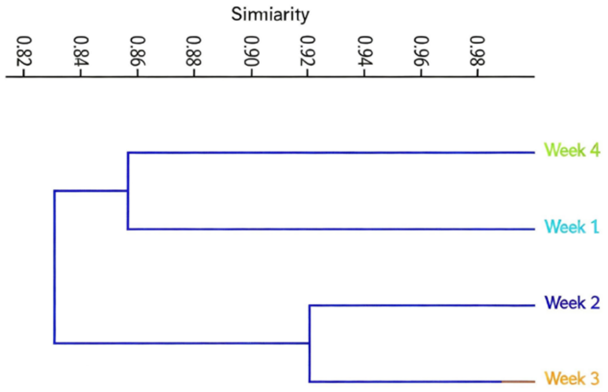

Fig. 3. Cluster Analysis between Weeks using Bray-Curtis Similarities from √-Transformed Visitors density data

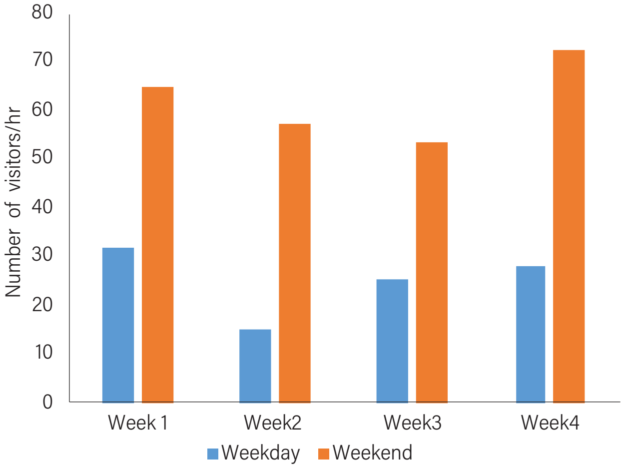

Fig. 4. Variation in the Visitors/hour between weekdays and within the weeks

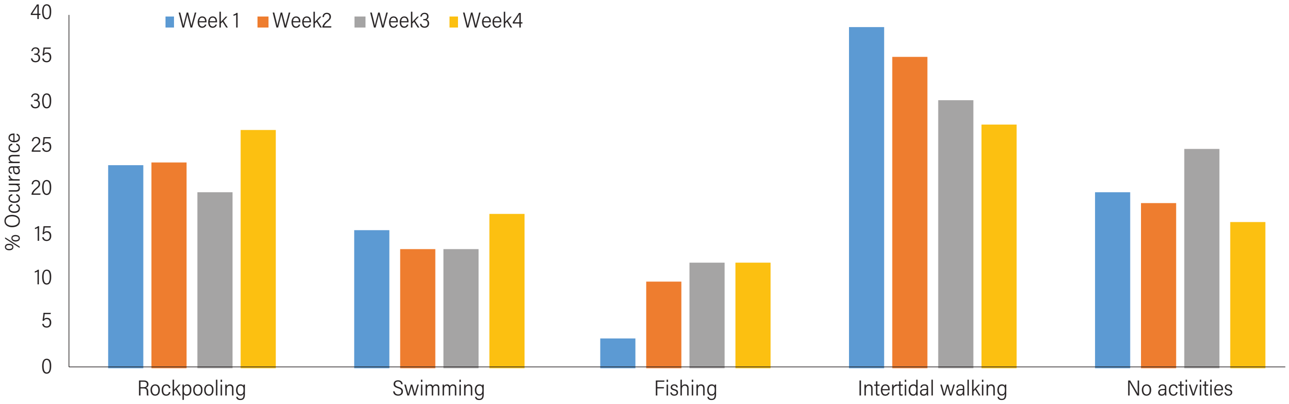

Fig. 5. Illustrations represent the variations in activities

damage than children, likely due to higher static pressure (trampling), which is known to crush barnacles and displace sessile epibiota. Non-Metric MDS (Fig. 6) identifies intertidal walking as the prominent activity. A direct correlation was observed between activities, visitor numbers, and ecosystem damage; as foot traffic increases, it leads to the loss of foliose algae and the depletion of large, dominant individuals, thereby destabilising the intertidal community structure.

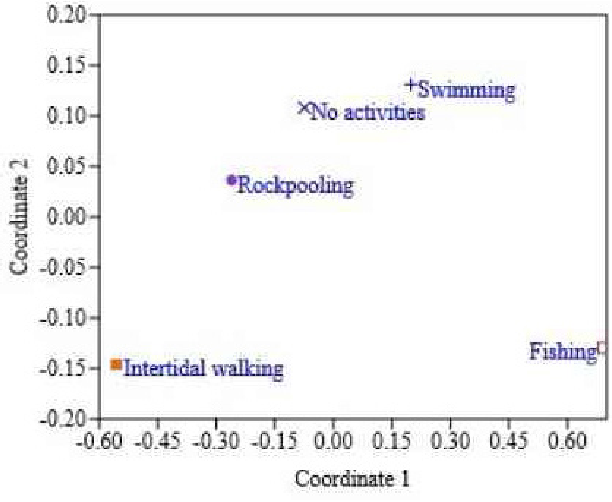

Fig. 6. Non-metric MDS plot establishing the deviations between the activities

Biodiversity

A total of 24 species, belonging to 20 genera, 14 classes, 8 phyla, and 3 kingdoms, were identified (Fig. 7, Table 1). Seventeen species were identified to the species level, while seven were identified to the genus level. Taxa included Chlorophyta, Rhodophyta, Ochrophyta, Mollusca, Arthropoda, Chordata, Echinodermata, and Cnidaria. Fig. 8 illustrates the percentage composition of this biodiversity. The majority of recorded epibiota were sessile, resulting in minimal changes in species density and diversity over short intervals. Mollusca was the dominant taxon in terms of diversity (11 species; 46%), followed by Echinodermata (13%).

Seaweeds dominated the terrain in terms of density, followed by chitons. Macroalgae such as *Jania adhaerens* and *Acanthophora spicifera* occupied the entire habitat (Fig. 9a

Table 1. Intertidal biodiversity along the Magna coast, Saudi Arabia

Kingdom	Phylum	Class	Genus	Species	Density (No./m^2)	IUCN Status
Plantae	Chlorophyta	Ulvophyceae	*Valoniopsis*	*Valoniopsis pachynema*	4	LC
Plantae	Rhodophyta	Florideophyceae	*Jania*	*Jania adhaerens*	7	LC
Plantae	Rhodophyta	Florideophyceae	*Acanthophora*	*Acanthophora spicifera*	18	LC
Chromista	Ochrophyta	Phaeophyceae	*Turbinaria*	*Turbinaria ornata*	4	LC
Chromista	Ochrophyta	Dictyotaceae	*Padina*	*Padina* sp.	12	LC
Animalia	Mollusca	Polyplacophora	*Acanthopleura*	*Acanthopleura testudo*	14	LC
Animalia	Mollusca	Polyplacophora	*Acanthopleura*	*Acanthopleura vaillianti*	6	LC
Animalia	Mollusca	Ophiuroidea	*Ophiocoma*	*Ophiocoma erinaceus*	2	LC
Animalia	Mollusca	Ophiuroidea	*Ophiocoma*	*Ophiocoma dentata*	4	LC
Animalia	Mollusca	Gastropoda	*Clypeomorus*	*Clypeomorus bifasciata bifasciata*	5	LC
Animalia	Mollusca	Gastropoda	*Nerita*	*Nerita undata*	2	LC
Animalia	Mollusca	Gastropoda	*Nerita*	*Nerita* sp.	3	LC
Animalia	Mollusca	Gastropoda	*Turbo*	*Turbo argyrostomus*	1	LC
Animalia	Mollusca	Gastropoda	*Planaxis*	*Planaxis sulcatus*	29	LC
Animalia	Mollusca	Gastropoda	*Engina*	*Engina mendicaria*	2	LC
Animalia	Mollusca	Bivalvia	*Pinna*	*Pinna* sp.	1	LC
Animalia	Arthropoda	Malacostraca	*Grapsus*	*Graspus graspus*	1	LC
Animalia	Arthropoda	Thecostraca	*Balanus*	*Balanus* sp.	5	LC
Animalia	Chordata	Teleostei	*Parapercis*	*Parapercis nebulosa*	1	LC
Animalia	Echinodermata	Holothuroidea	*Holothuria*	*Holothuria forskali*	1	LC
Animalia	Echinodermata	Holothuroidea	*Holothuria*	*Holothuria* sp.	1	LC
Animalia	Echinodermata	Echinoidea	*Stomopneustes*	*Stomopneustes variolaris*	1	LC
Animalia	Cnidaria	Scleractinia	*Porites*	*Porites* sp.	1	NT
Animalia	Cnidaria	Scleractinia	*Acropora*	*Acropora* sp.	5	NT

to 9c). These species function as ecosystem bioengineers, providing critical protection from thermal stress and water loss for associated macroinvertebrates. An IUCN status analysis indicated most species are of Least Concern, though Cnidarians such as *Porites* sp. and *Acropora* sp. are classified as Near Threatened. No invasive species, such as Codium

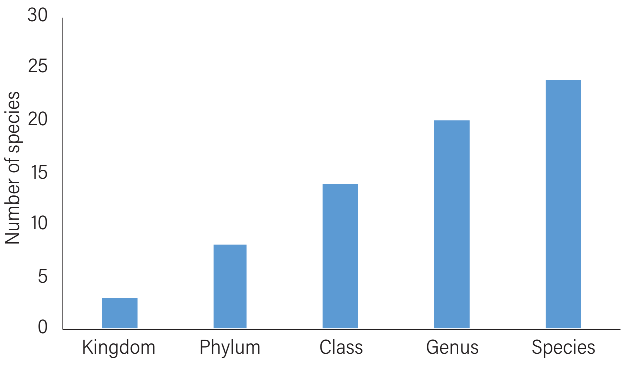

Fig. 7. Differences in the taxon along the Intertidal coast of Magna, Saudi Arabia

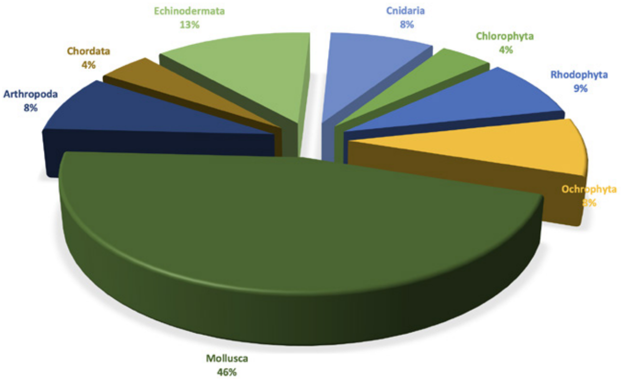

Fig. 8. Percentage composition of the intertidal biodiversity along the coast of Magna, Saudi Arabia

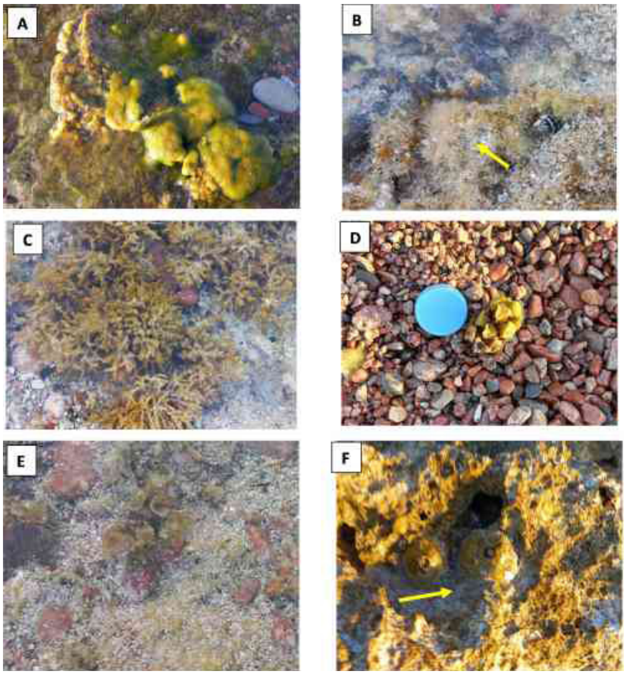

Fig. 9a. List of species identified along the Study area, A- *Valoniopsis pachynema,* B- *Jania adhaerens,* C- *Acanthophora spicifera,* D- *Turbinaria ornate,* E- *Padina* sp., F- *Balanus* sp.

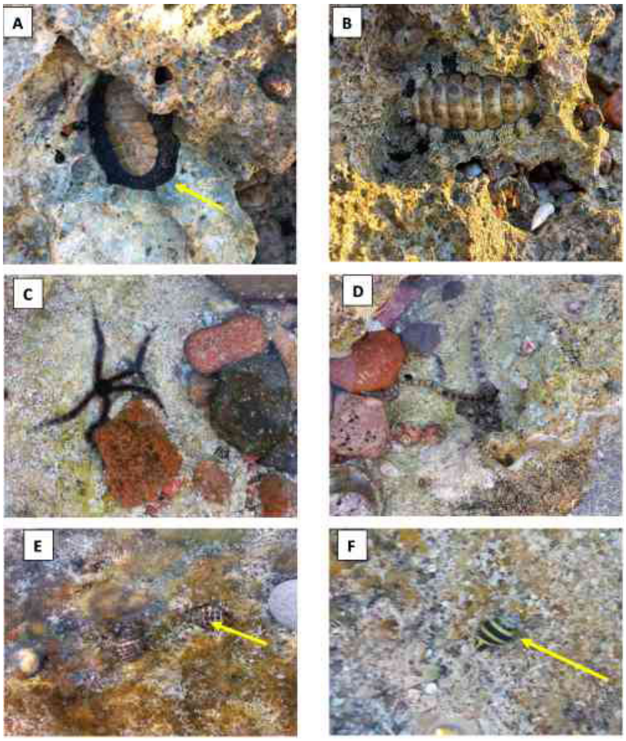

Fig. 9b. List of species identified along the Study area, A- *Acanthopleura testudo,* B- *Acanthopleura vaillianti,* C- *Ophiocoma erinaceus,* D- *Ophiocoma dentate,* E- *Clypeomorus bifasciata bifasciata,* F- *Engina mendicaria*

fragile, were identified, which is vital for maintaining the native resilience of the Red Sea's unique intertidal zones

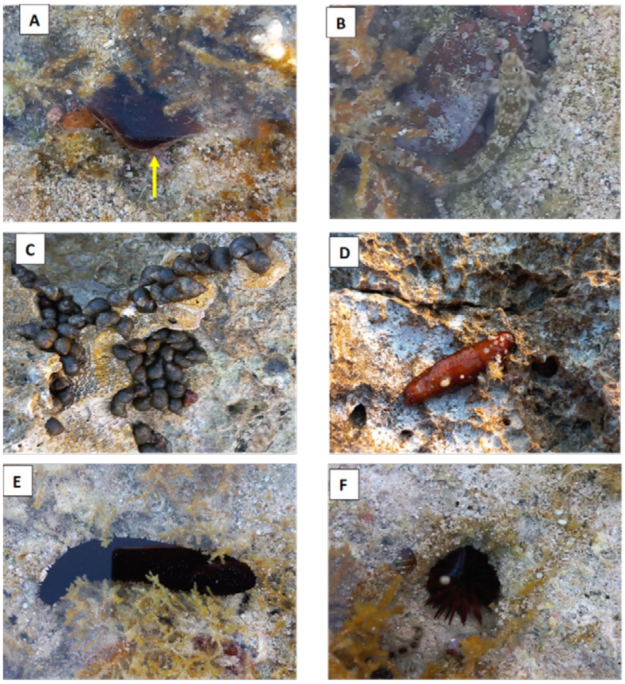

Fig. 9c. List of species identified along the Study area, A- *Pinna* sp, B- *Parapercis nebulosa,* C- *Planaxis sulcatus,* D- *Holothuria* sp., E- *Holothuria forskali,* F- *Stomopneustes variolaris*

Discussion

Limited information is available on the taxonomy, distribution, abundance, and non-indigenous species of intertidal fauna along the coast of Magna. With the rapid development of the Kingdom of Saudi Arabia's tourism sector and the recent increase in outdoor activities, the potential impacts of tourism on marine biodiversity remain understudied (Eckrich and Holmquist, 2000; Schlacher *et al*., 2013). This study represents a pioneering effort to address this knowledge gap by investigating the impacts of tourism on marine biodiversity and tracing the subsequent effects through ecotourism policies. It is important to note that the coastal region of Saudi Arabia is home to a diverse array of endemic and endangered species. The shift in species diversity and reduction in density were among the more common effects observed due to frequent recreational activities. This assessment will serve as a tool to strengthen existing ecotourism policies.

The intertidal fauna of the Magna coast remains taxonomically understudied, particularly regarding the distribution of non-indigenous species (NIS) and the abundance of endemic taxa. This study identifies a distinct pulse disturbance pattern (Mendez *et al*., 2017), where visitor counts surge during weekends. Such fluctuations mirror the findings of Pinn and Rodgers (2005), suggesting that recreational pressure is not a constant stressor but a series of high-intensity events.

The ecological danger of these "pulses" is that the recovery time for intertidal assemblages often exceeds the interval between disturbances. Bravo *et al.* (2015) demonstrated that macroalgal recovery and invertebrate recolonisation cycles are frequently interrupted by weekly high-traffic events, leading to a state of chronic degradation despite the seemingly "low" average monthly visitor counts (87 visitors/hour).

Despite the Kingdom of Saudi Arabia launching numerous initiatives such as the Saudi Green Initiative, CORDAP, Vision 2030, and Net Zero Emission to safeguard terrestrial and marine biodiversity, the cumulative long-term impacts of visitors could lead to chronic and persistent damage to the ecosystem (Davenport and Davenport, 2006).

Common activities among visitors included rock pooling, intertidal walking, swimming, and fishing. Intertidal walking was identified as the most pervasive activity. While often perceived as benign, the cumulative mechanical stress of trampling triggers significant structural changes in the community. Our observations of the vulnerability of branching macroalgae align with the findings of Povey and Keough (1991) and Jenkins *et al.* (2020), which indicate that upright, branching taxa are more susceptible to breakage than prostrate or turf-forming species.

The replacement of canopy-forming algae (*Jania adhaerens*) with opportunistic ephemeral species often leads to a reduction in habitat complexity. This loss of "biogenic housing" directly impacts the recruitment of juvenile invertebrates, potentially leading to a localised decline in biodiversity. The extraction of gastropods and limpets for bait or food, observed primarily among adult visitors, removes top-down grazers. This removal can trigger trophic cascades, where the absence of herbivores allows algal biofilms to overgrow and outcompete sessile calcifiers for space (Dutton *et al*., 2005).

Based on the collected data, a One-way Analysis of Variance (ANOVA) revealed that visitor counts were significantly higher on weekends ($p<0.05$) compared to weekdays. The Non-Metric Multidimensional Scaling (nMDS) ordination (Fig. 6) provided a clear spatial representation of activity deviations, with a low stress value (< 0.1), indicating a highly reliable fit of the data. The nMDS plot clearly separated "intertidal walking" as the most distinct and prominent cluster, showing a high degree of centroid grouping across all sampled weeks. This statistical relationship confirms that as visitor numbers increase, the integrity of the ecosystem decreases in a linear, predictable fashion.

Studies on the impacts of trampling on rocky shores have shown a sharp reduction in the density of larger and branching macroalgae alongside an increase in turf species (Povey and Keough, 1991; Fletcher and Frid, 1997; Keough and Quinn, 1998; Jenkins *et al*., 2020). Supporting this research, in the current study, the area was noted to be flourishing with branching macroalgae alongside high rates of intertidal walking. As mentioned earlier, tourism may lead to alterations in the macroalgal communities, which in turn could impact the entire ecosystem. Furthermore, ephemeral algal species tend to be more abundant in areas of heavy activity (Fletcher and Frid, 1997).

The Magna coast serves as a critical refuge for Near Threatened scleractinian corals, including *Porites* sp. and *Acropora* sp. These species exist at their physiological limits during low tide, facing extreme thermal stress and desiccation. When recreational trampling is superimposed on these environmental stressors, the metabolic cost of repair may exceed the energy budget of the coral, leading to localised extinction (Bogorodsky, 2019). The presence of these species underscores the urgent need for ecotourism-specific zoning, as even low levels of trampling can cause irreversible damage to slow-growing coral recruits that are essential for the reef's long-term accretion.

The "pulse disturbance" identified in this study is statistically characterised by high temporal variance. The similarity indices shown in Fig. 3 (Bray-Curtis Similarity) suggest that while the biological community remains relatively stable during the week, the weekend surge causes a significant dissimilarity shift in the benthic cover. This suggests that the ecosystem is experiencing "Statistical Homogenization," where sensitive, branching species are being filtered out, leaving. A general lack of knowledge and awareness regarding the importance of intertidal communities contributes significantly to these impacts. Ecotourism is considered a viable option to mitigate these impacts and protect marine biodiversity, aligning with Saudi Vision 2030 ambitious goal of safeguarding 30% of Saudi Arabia's land and sea (Saudi Green Initiative, 2024). Recent awareness of biodiversity sustainability, along with developments in the Red Sea region such as NEOM and the JCPDI (RCJY), has led to the incorporation of sustainability goals into master plans aimed at protecting ecosystems. One of the main responses to combat threats to biodiversity is the conversion of biodiversity-rich areas into protected reserves (Gossling, 1999).

Saudi Arabia's transition toward a "blue economy" through Vision 2030 and the Saudi Green Initiative has catalysed a massive expansion of protected areas, now covering approximately 14.9% of the Kingdom's territory (Vision 2030 Annual Report, 2023). However, as Davenport and Davenport (2006) argue, the mere designation of protected areas is insufficient without active enforcement and monitoring.

Table 2: List of recommendations to implement

Management category	Observed impact	Proposed intervention	Strategic alignment
Zoning & access	Weekend visitor spikes (310/hr) are causing mechanical stress.	Implement Spatiotemporal Zoning; restrict access to sensitive reef flats during low-tide peaks and weekend "pulse" periods.	Saudi Green Initiative: Sustainable Tourism.
Physical infrastructure	Trampling of *Porites* and *Acropora* sp.	Installation of elevated eco-walkways or floating pontoons to eliminate direct contact with the substrate.	NEOM Nature: 95% Conservation Commitment.
Resource protection	Extraction of limpets and gastropods for bait/food.	Establish "No-Take" Marine Micro-Reserves to preserve top-down grazers and prevent trophic cascades.	Vision 2030: Biodiversity Protection.
Public engagement	Lack of awareness regarding sessile epibiota.	Deployment of Smart-Signage (QR-coded) and "Intertidal Rangers" to educate visitors on the "Don't Turn the Rock" principle.	Saudi Vision 2030: Quality of Life Program.
Technological monitoring	Inability to track real-time ecosystem shifts.	Use of AI-driven computer vision (NEOM's digital infrastructure) to monitor visitor density and detect unauthorised harvesting.	Cognitive Cities (NEOM): Data-driven conservation.

To meet the goal of protecting 30% of marine domains by 2030, coastal developments like NEOM and JCPDI must move beyond traditional conservation. Our results suggest that a lack of public awareness is a primary driver of ecosystem damage. Implementing "Citizen Science" programs and educational signage could mitigate the impacts observed in this study.

While the Saudi Green Initiative and CORDAP provide a high-level framework, local authorities must implement site-specific regulations (*e.g.,* seasonal closures during spawning periods) to prevent the "pulse" disturbances from becoming permanent ecological shifts. To mitigate the observed impacts of "pulse disturbances" and unregulated intertidal activities, the following management strategies are recommended for the Magna coast (Table 2).

Conclusion

In conclusion, the intertidal ecosystem of Saudi Arabia, while providing essential ecological services, is increasingly subjected to anthropogenic pressures driven by expanding coastal tourism. The study clearly demonstrates that intensified recreational activities—particularly weekend "pulse disturbances"—and projected high visitor densities under developments such as NEOM lead to measurable ecological impacts, including physical damage to sessile epibiota and a decline in branching macroalgae. Despite ongoing sustainability-oriented initiatives, including Jazan City for Primary and Downstream Industries, the findings underscore that current and future tourism pressures pose significant risks to sensitive intertidal habitats, especially those harbouring endemic and threatened species. Therefore, achieving a balance between development and conservation necessitates a holistic management framework integrating ecotourism principles, continuous ecological monitoring, targeted conservation strategies, public awareness, and strict regulation of visitor intensity and activities. Such measures are critical to safeguarding the long-term health and resilience of intertidal ecosystems.

Author contributions

Conceptualisation: NG, TAJ, KPK; Methodology: NG, RSA; Data collection: NG, RSA; Data analysis: NG, RSA; Writing original draft: NG, TAJ, KPK; Writing review and editing: TAJ, KPK; Supervision: NG

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of samples/ protected environments.

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Publisher's note

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Biometric characteristics of *Megalaspis cordyla* (Linnaeus, 1758) in the Chennai coastal waters, India

K. Silambarasan[1]*, R. John Peter[2], A. Tiburtius[3], Y. Tharumar[2] and K. R. Sreenath[3]
[1]Zoological Survey of India, Andaman and Nicobar Regional Centre, Andaman and Nicobar Islands, Port Blair-744 102, India.
[2]Fishery Survey of India, Royapuram, Chennai, Tamil Nadu - 600 013, India.
[3]Fishery Survey of India, New Fishing Jetty, Sasson Dock, Colaba, Mumbai- 400 005, India.

*Correspondence e-mail: silambuplankton@hotmail.com
ORCiD: https://orcid.org/0000-0001-5805-1562

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Original Article

Abstract

The biometric characteristics of the horse mackerel, *Megalaspis cordyla* (Linnaeus, 1758) from the Chennai coastal waters, Southeastern India, were investigated to examine morphometric variation and to provide baseline biometric information for the species. A total of 411 specimens, ranging in total length from 16.6 to 43.6 cm and in weight from 42.0 to 630.0 g, were collected monthly between April 2023 and March 2024. Fifteen morphometric and seven meristic characters were measured and analysed using standard statistical methods. The coefficients of variation for morphometric traits ranged from 9.51% to 21.64%, while those for meristic traits ranged from 4.76% to 16.11%. Highly significant positive correlations ($p < 0.01$) were observed among key morphometric traits, particularly between total length and fork length, standard length, and snout to pelvic distance. In contrast, post-orbital length, snout length, and eye diameter exhibited relatively slower growth. The fin formula was observed to be: D_1 VII-VIII, D_2 I + 10–11, followed by 6–9 dorsal finlets; P 10-22, V I + 4–5, A I + 6-17, followed by 6–8 ventral finlets. Principal component analysis (PCA) was conducted on 15 allometrically size-corrected morphometric variables to identify the major contributors to morphological variation in *M. cordyla.* The first principal component (PC1) explained 29.53% of the total variance, with the highest loadings observed for TL, FL, and interdorsal space. The relatively narrow variation and strong interrelationships among morphometric characters indicated limited morphological variability among the sampled specimens. These findings provide baseline morphometric and meristic data for future comparative studies and may support further investigation on population structure and stock assessment of the species.

Keywords: *Morphometry, meristics, stock structure, fishery management, Chennai coast*

Introduction

Understanding the population structure of an exploited resource is a critical aspect of effective fisheries management. This information is particularly valuable for defining suitable conservation units and for estimating stock structure in multispecies fisheries. Fish stocks are typically distinguished by their structural and biological characteristics. The traits used to differentiate stocks may be influenced by genetic factors, environmental conditions, or both (Swain *et al.,* 2005).

Morphometric and meristic characters are frequently used to delineate the stocks of various exploited fish species (Murta, 2000; Silva, 2003; Turan, 2004). These characters are also useful for assessing the degree of differentiation and relationship among various taxa, as well as for describing their spatial distribution (Ihseen *et al.,* 1981). Morphometrics, which combines principles of geometry with biological study, provides valuable insights into the shape and structure of organisms (Bookstein, 1997). In fish, variations in morphometric traits often reflect differences in growth patterns and maturation rates, as body shape is closely linked to developmental processes. The adaptive changes, including phenotypic plasticity, may influence their external appearance, reproductive strategies, or survival, helping them cope with environmental challenges (Stearns, 1983; Meyer, 1987).

The meristic characters are widely used to assess the stock status of fish populations. Commonly recorded features include the number of spines and rays, gill rakers and scales. Meristic analysis has long been considered a fundamental approach for identifying fish stocks. Many species with multiple stocks, and

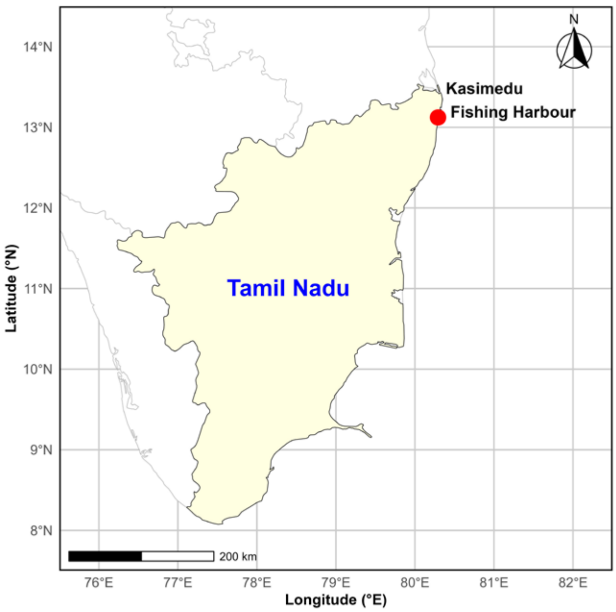

Fig. 1. Map showing the sampling location of Kasimedu fisheries harbour, Chennai coast

that are subject to fishery management, have received at least some level of meristic analysis (Waldman, 2005). Morphometric and meristic traits are often analysed together to gain a more comprehensive understanding of population structure.

The genus *Megalaspis* (Family: Carangidae) is monotypic, containing only a single species, *Megalaspis cordyla* (Linnaeus, 1758). It is a relatively large schooling species and is considered a high-quality table fish in the Indian pelagic fisheries sector. The species is primarily found in the Indo-Pacific region (Froese and Pauly, 2024). During the period 2020-21, *M. cordyla* contributed approximately 0.83 lakh tons to the total marine fish landings in India (DoF, 2022). Morphometric and meristic studies on the horse mackerel *M. cordyla* are limited, with only a few studies conducted in Indian waters (Jaiswar and Devaraj, 1989; Jaiswar and Acharya, 1991; Saker *et al.,* 2004; Sajina *et al.,* 2013). These studies were mainly conducted in other regions of India, and similar information from the Chennai coast along the southeastern Bay of Bengal remains limited. Therefore, the present study was conducted as a preliminary investigation to establish baseline morphometric and meristic data for *M. cordyla* from the Chennai coastal waters, Southeastern India.

Material and methods

A total of 411 specimens of *M. cordyla* were obtained through fishery-dependent sampling from the Kasimedu fish landing centre (13°07.32′N/80°17.49′E), located along the Chennai coastal waters (Fig. 1), during the period from April 2023 to March 2024. The lengths of the specimens ranged from 16.6 to 43.6 cm (25.0 ± 2.82 cm), and their weight ranged from 42.0 to 630.0 g (151.43 ± 59.50 g). The species was primarily caught in commercial trawl landings using various types of trawl nets with mesh sizes ranging from 20 to 30 mm. The total length of each individual was measured from the tip of the snout to the end of the tail to the nearest 0.1 mm, and the body weight was recorded using an electronic weighing balance with an accuracy of 0.01 g. A total of 15 morphometric (Fig. 2) and 07 meristic characters were examined following

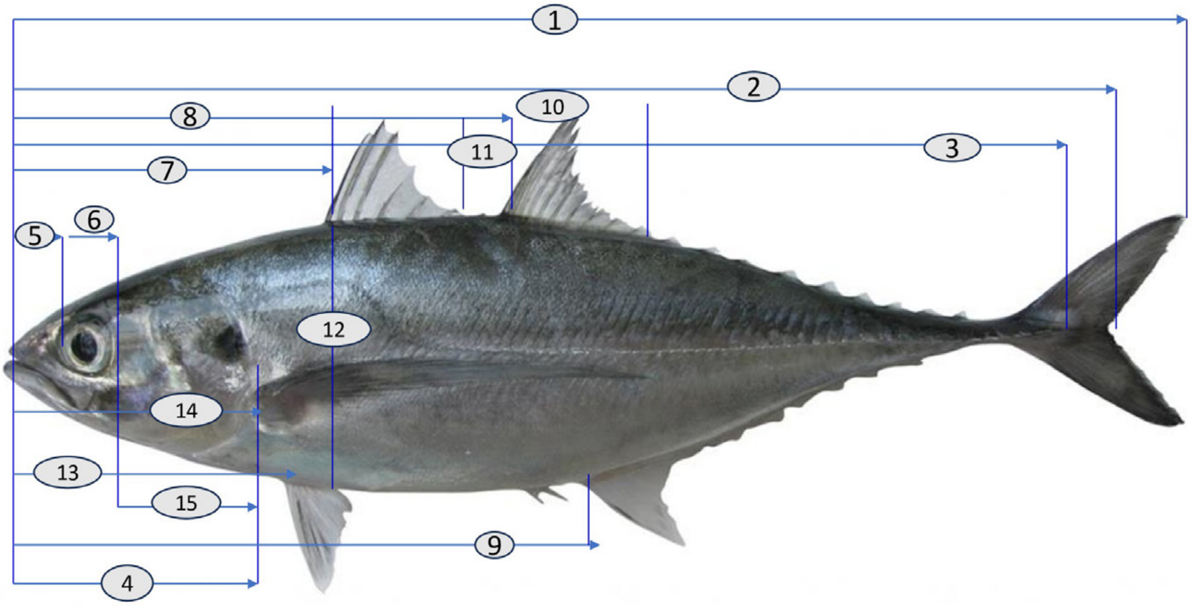

Fig. 2. Morphometric characters of *M. cordyla*. 1. Total length (TL), 2. Fork length (FL), 3. Standard length (SL), 4. Head length (HL), 5. Snout length (SnL), 6. Eye diameter (ED), 7. Snout to first dorsal, 8. Snout to second dorsal, 9. Snout to anal, 10. First dorsal to second dorsal, 11. Interdorsal space, 12. Body depth (BD), 13. Snout to pelvic, 14. Snout to pectoral, 15. Post-orbital length

the standard methodologies described by Laevastu (1965), Lowe-McConnel (1971), Dwivedi and Menezes (1974) and Grant and Spain (1977). To analyze the morphometric characters, scatter plots were generated to examine the relationships among variables, and linear regression equations of the form $Y = a + bX$ (where, Y is the dependent variable, X is the independent variable, a is the intercept, and b is the slope) were fitted using the least squares method, as outlined by Laevastu (1965) and Snedecor and Cochran (1967).

Meristic characters, such as the number of spines and soft rays on the dorsal, pectoral, pelvic, anal, and caudal fins, were recorded. These counts were performed using a magnifying lens and a fine needle to distinguish individual rays. Relationships between various morphometric traits and total length, as well as head length, were analysed. For both morphometric and meristic characters, descriptive statistics, including mean, range, standard deviation, standard error and coefficient of variation, were calculated.

To remove the effect of body size on morphometric characters, all measurements were standardised using the allometric adjustment method following Reist (1985); Quilang *et al.* (2007).

$$M_{adj} = \log Y - b\,(\log X - \log X_{STL})$$

Where, M_{adj} = size-adjusted morphometric measurement; Y = original unadjusted morphometric measurement; b = allometric coefficient (slope of the regression of log Y against log X); X = standard length of the specimen; X_{STL} = mean standard length of all specimens examined; *log* = base-10 logarithm.

After size correction, Principal Component Analysis (PCA) was applied to the size-adjusted morphometric data to identify the major contributors to morphological variation among specimens. PCA reduces multidimensional morphometric variables into a smaller number of independent components, thereby identifying the characters that contribute most to the observed variations (Konan *et al.,* 2010). All statistical analyses were performed using R version 4.3.2 (R Core Team, 2023).

Results

The morphometric study was carried out on 411 specimens of horse mackerel, *Megalaspis cordyla* collected from the Chennai coastal waters. The total length of the specimens ranged from 16.6 cm to 43.6 cm. Descriptive statistics, including mean, standard deviation, standard error and coefficient of variation, are presented in Table 1. The results showed that the highest coefficient of variation (%) was observed in snout length (21.64%), followed by interdorsal space (16.14%), snout to pectoral (12.18%), *etc.*

The simple linear regression equations are presented in Table 2. The highest regression coefficient ('b') value was observed for fork length (0.9073), followed by standard length (0.8298), snout length (0.4380), snout to anal (0.3974) and the

Table 1. Summary of descriptive statistics for the Morphometric measurements of *Megalaspis cordyla*

Morphometric characters	Range (cm)	Mean (cm)	SD	Standard error	CV (%)
Total length	16.6-43.6	25	2.82	0.15	11.27
Fork length	15.5-40.5	23.04	2.6	0.14	11.29
Standard length	13.5-37.3	20.84	2.4	0.13	11.53
Head length	3.7-9.2	5.54	0.57	0.03	10.35
Snout length	0.8-2.9	1.42	0.31	0.02	21.64
Eye diameter	0.7-2	1.16	0.14	0.01	12.34
Postorbital length	2.2-4.3	2.96	0.3	0.02	10.15
Snout to 1st Dorsal	4.4-12	6.76	0.83	0.04	12.26
Snout to 2nd dorsal	6.7-17.5	10.03	1.18	0.06	11.77
Snout to anal	6.8-18.4	10.63	1.26	0.07	11.83
1st dorsal to 2nd dorsal	2.4-6.2	3.46	0.43	0.02	12.34
Inter-dorsal space	0.4-1.6	0.79	0.13	0.01	16.14
Body depth	4.2-10	6.19	0.59	0.03	9.51
Snout to Pelvic	4.00-9.00	6.24	0.71	0.04	11.41
Snout to pectoral	3.8-9.5	5.55	0.68	0.04	12.18

Table 2. Linear regression values describing the relationship among different morphometric measurements of *M. cordyla*

Morphometric Characters	Equation	r	p-value
Fork length and total length	$Y = 0.3570 + 0.9073X$	0.967	<0.0001
Standard length and total length	$Y = 0.0967 + 0.8298X$	0.948	<0.0001
Head length and total length	$Y = 0.9378 + 0.1840X$	0.818	<0.0001
Snout length and total length	$Y = -1.0639 + 0.0993X$	0.831	<0.0001
Eye diameter and total length	$Y = 0.0001 + 0.0462X$	0.835	<0.0001
Snout 1stdorsal and total length	$Y = -0.0184 + 0.2712X$	0.85	<0.0001
Snout 2nd dorsal and total length	$Y = 0.4785 + 0.3823X$	0.832	<0.0001
Snout anal and total length	$Y = 0.6915 + 0.3974X$	0.794	<0.0001
1stdorsal to 2nd dorsal and total length	$Y = 0.0252 + 0.1372X$	0.823	<0.0001
Inter dorsal space and total length	$Y = -0.3093 + 0.0441X$	0.943	<0.0001
Body depth and total length	$Y = 1.3606 + 0.1933X$	0.856	<0.0001
Snout pelvic and total length	$Y = 0.3205 + 0.2367X$	0.878	<0.0001
Snout pectoral and total length	$Y = -0.0405 + 0.2236X$	0.87	<0.0001
Eye diameter and head length	$Y = 0.0049 + 0.2078X$	0.698	<0.0001
Snout length and head length	$Y = -1.0067 + 0.4380X$	0.669	<0.0001
Postorbital length and head length	$Y = 1.0018 + 0.3541X$	0.456	<0.0001

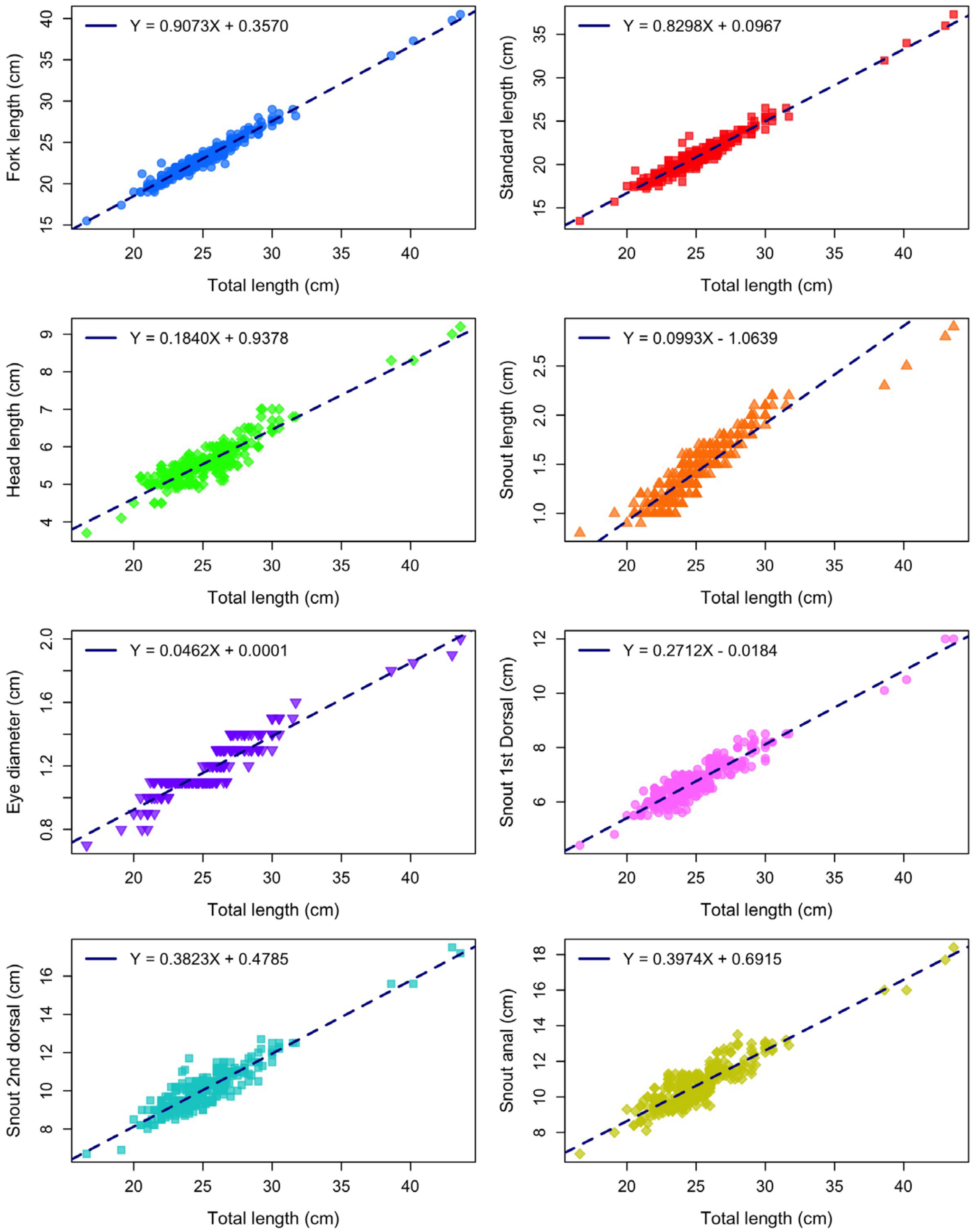

Fig. 3. Scatter plot showing the relationship between total length and different morphometric measurements of *M. cordyla*

lowest for interdorsal space (0.0441), when compared with total length (Fig. 3). Similarly, when morphometric characters compared against head length, the highest growth rate ('b') was observed in snout length (0.4380), followed by post-orbital length (0.3541) and eye-diameter (0.2078).

The correlation coefficient (r) values ranged from 0.456 to 0.967, indicating significant positive relationships among all morphometric characteristics of *M. cordyla* with total length ($p < 0.01$). The Pearson correlation matrix for the various morphometric measurements is presented in Table 3. Fork length exhibited the strongest correlation with total length (0.967), while post-orbital length showed the weakest correlation (0.456). In addition, the correlation of head length with other morphometric characters was highest with eye diameter (0.698) and lowest with post orbital length (0.456) (Fig. 4).

Principal component analysis (PCA) was performed on 15 size-corrected morphometric variables to identify the major contributors to morphological variations in *M. cordyla* (Table 4). The analysis produced 15 principal components, corresponding to the number of variables included in the dataset. Among these, the first three principal components together explained 55.4% of the total variance. The first principal component (PC1) accounted for 29.53% of the total variance and showed the highest loadings for TL, FL, and interdorsal space. Similarly, the second principal component (PC2) explained 16.0% of the total variance, with the highest loadings for snout to anal, 1st dorsal to anal, and 2nd dorsal to anal distances. The third principal component (PC3) accounted for 9.9% of the total variance and was mainly associated with snout length, the distance from the snout to the first dorsal fin, and the distance from the snout to the second dorsal fin. The relatively lower contributions of PC2 and PC3 compared to PC1 suggest that

Table 4. Component loadings of the first three principal components for morphometric measurements of *M. cordyla* from Chennai coastal waters

Character/Variable	Load value		
	PC1	PC2	PC3
Total Length	-0.412*	0.147	0.216
Fork length	-0.317*	0.065	0.052
Snout Length	-0.201	0.194	0.300*
Eye diameter	-0.225	-0.034	-0.100
Head Length	-0.118	0.190	0.010
Snout to 1st dorsal	-0.295	-0.146	-0.426*
Snout to 2nd dorsal	-0.281	-0.091	-0.543*
Snout to anal	-0.252	-0.430*	-0.163
1st dorsal to 2nd dorsal	-0.222	-0.027	0.053
1st dorsal to anal	-0.103	-0.543*	0.275
2nd dorsal to anal	-0.060	-0.561*	0.279
Inter dorsal space	-0.332*	0.177	0.242
Body depth	-0.265	-0.004	0.189
Snout to pelvic	-0.296	0.139	0.176
Snout to pectoral	-0.252	0.155	-0.257
Eigen values	4.430	2.396	1.486
Contribution rate (%)	29.53	15.97	9.91
Cumulative contribution rate (%)	29.53	45.50	55.41

Table 3. Pearson's correlation matrix showing relationships among different morphometric measurements of *M. cordyla*

	TL	Wt	FL	SL	SnL	ED	HL	Sn.1D	Sn.2D	Sn.A	X1D.2D	IDS	BD	Sn.Pel	Sn.pec	POL
TL	1	0.937 **	0.983 **	0.973 **	0.658 **	0.582 **	0.867 **	0.884 **	0.911 **	0.854 **	0.844 **	0.406 **	0.768 **	0.815 **	0.831 **	0.376 **
Wt	-	1	0.948 **	0.942 **	0.63 **	0.544 **	0.856 **	0.857 **	0.886 **	0.841 **	0.825 **	0.437 **	0.774 **	0.792**	0.82 **	0.467 *
FL			1	0.985 **	0.658 **	0.575 **	0.87 **	0.89 **	0.914 **	0.861 **	0.847 **	0.422 **	0.775 **	0.829 **	0.842 **	0.407 *
SL				1	0.649 **	0.566 **	0.87 **	0.881**	0.905 **	0.854 **	0.838 **	0.424 **	0.77 **	0.825 **	0.834 **	0.407 *
SnL					1	0.372 **	0.657 **	0.626**	0.588 **	0.551 **	0.574 **	0.277 **	0.508 **	0.592 **	0.608 **	0.323 **
ED						1	0.436 **	0.539**	0.538 **	0.577 **	0.558 **	0.393 **	0.505 **	0.454 **	0.479 **	0.13 *
HL							1	0.794**	0.814 **	0.747 **	0.774 **	0.291 **	0.704 **	0.742 **	0.75 **	0.667 **
Sn.1D								1	0.947 **	0.88 **	0.778 **	0.405 **	0.782 **	0.833 **	0.833 **	0.351**
Sn.2D									1	0.899 **	0.815 **	0.376 **	0.765 **	0.856 **	0.866 **	0.37 **
Sn.A										1	0.766 **	0.555 **	0.811 **	0.775 **	0.776 **	0.325 **
X1D.2D											1	0.432 **	0.683 **	0.74 **	0.754 **	0.395 **
IDS												1	0.477 **	0.334 **	0.346 **	0.102 -
BD													1	0.702 **	0.723 **	0.359 **
Sn.Pel														1	0.946 **	0.34 **
Sn.pec															1	0.334 **
POL																1

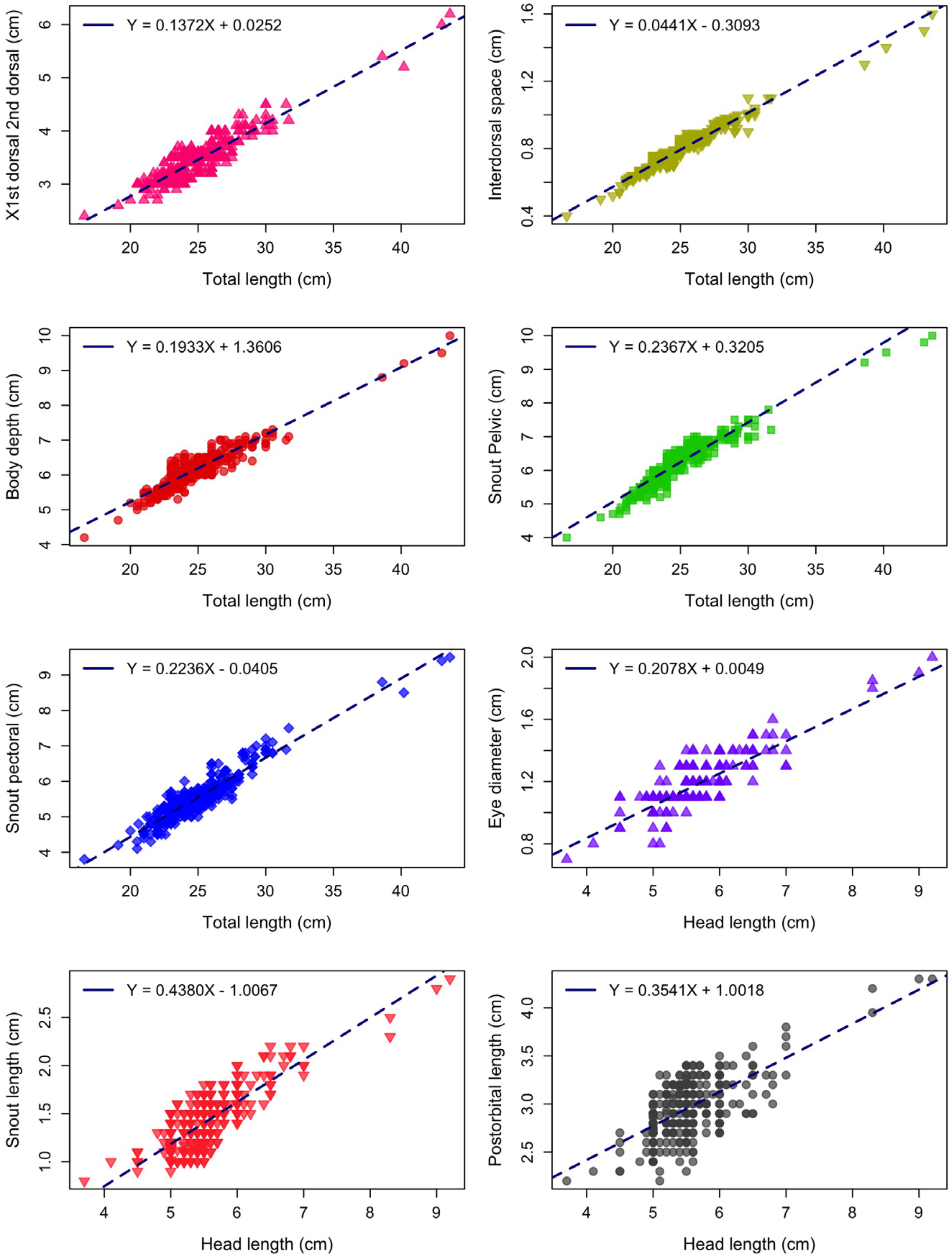

Fig. 4. Scatter plot showing the relationship between total length and different morphometric measurements of *M. cordyla*

these components represent minor morphological differences. Conversely, PC1 reflects the primary morphological gradient and predominantly illustrates the overall body-shape trend in *M. cordyla*.

The PCA based cluster analysis indicated the presence of three different morphometric groups within the *M. cordyla* population, reflecting variation in body elongation, trunk structure, and fin positioning (Fig. 5). The first cluster comprised individuals with intermediate body proportions, the second cluster consisted of more elongated individual with higher PC1 scores, and the third cluster included fish with lower PC2 values, indicating differences in trunk and ventral body proportions. The partial overlap observed among the clusters suggests that these groups represent natural morphological variability within the population rather than completely distinct morphotypes.

The range, mean, mode, median, standard deviation, standard error and coefficient of variation for various meristic characters are shown in Table 5. It was observed that the first dorsal fin has 7 to 8 spines, while the second dorsal fin has 01 spine followed by 10-11 soft rays. The pectoral fin possesses branched fin rays ranging from 10 to 22. The pelvic fin contains 01 spine and 4-5 soft rays, and dorsal finlets ranged from 6 to 9; ventral finlets ranged from 6 to 8. The coefficient of variation was highest in anal fin rays (16.11%), followed by ventral finlets (11.91%), pelvic fin rays (11.11%) and was lowest in second dorsal spines and rays (4.76%).

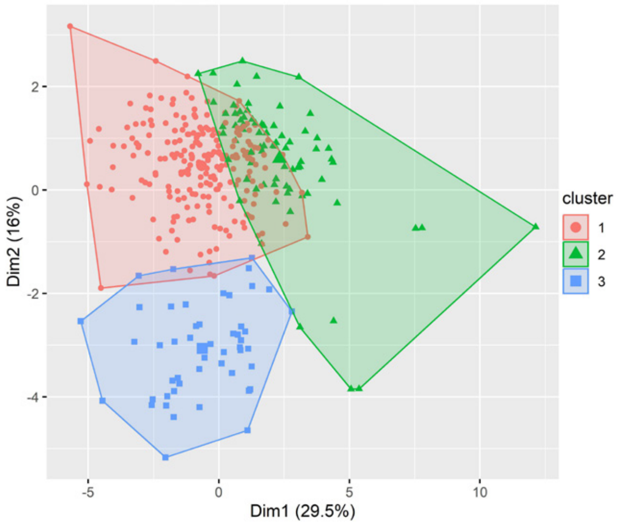

Fig. 5. The first and second principal component clusters of *M. cordyla* populations

Table 5. Statistical summary of meristic characters recorded for *M. cordyla*

Meristic characters	Range		Mean	Median	Mode	SD	SE	CV (%)
	Min	Max						
First dorsal fin spines	7.0	8.0	7.50	7.50	7.0	0.50	0.029	6.67
Second dorsal spines & rays	10.0	11.0	10.50	10.50	10.0	0.50	0.029	4.76
Pectoral fin rays	10.0	22.0	21.34	21.00	21.0	1.09	0.06	5.13
Pelvic fin rays	4.00	5.00	4.50	4.50	4.00	0.50	0.029	11.11
Anal fin rays	6.00	17.0	10.12	10.00	10.0	1.63	0.082	16.11
Dorsal finlets	6.00	9.00	7.91	8.00	8.00	0.47	0.03	5.99
Ventral finlets	6.00	8.00	7.35	7.00	7.00	0.87	0.05	11.91

Discussion

Fish morphometric studies are essential for accurate species identification and help in delineating different stock structures. In this study, the maximum size of *M. cordyla* was found to be 43.6 cm, which exceeds the maximum sizes reported in several earlier studies but is lower than the recorded 69.0 cm from the Gulf of Aden and the Red Sea (Al Sakaff and Esseen, 1999). However, the validity of this 69.0 cm record is doubtful. Conversely, Jaiswar and Devaraj (1989) reported a maximum length of 41.8 cm from the Northwest coast of India, while Sajina *et al.* (2013) observed a maximum size of 39.7 cm along the Indian coast, both comparable to the present study. Additionally, Sarmin *et al.* (2022) reported a maximum size of 36.5 cm for this fish from Bangladesh.

A comparison of morphometric measurements observed in the present study with those reported by Sajina *et al.* (2013) showed that the total length (TL) ranged from 16.3 to 39.7 cm, with specimens from the Mandapam region attaining a maximum TL of 31.6 cm. In contrast, the present study recorded a wider TL range of 16.0-43.6 cm, indicating the presence of larger individuals in the sampled population. Differences were also noticed in several morphometric characters. Sajina *et al.* (2013) reported eye diameter ranging from 0.81-1.50 cm for east coast specimens, whereas the present study recorded a slightly wider range of 0.7-2.0 cm. Further, head length reported by Sajina *et al.* (2013) ranged from 3.53-7.65 cm, while the present study reported higher values ranging from 9.2-9.7 cm. Similarly, the maximum body depth in Sajina *et al.* (2013) varied from 3.64 to 8.20 cm, whereas the present study recorded slightly higher values ranging between 4.2 and 10.0 cm.

The relatively higher morphometric ranges observed in the present study may primarily reflect the larger body size of the specimens examined, as morphometric measurements generally increase proportionally with the growth of the organisms (Froese, 2006). Such variations may be attributed to ecological conditions, food availability, prey density, and environmental characteristics along different coastal regions, which can contribute to phenotype plasticity in fish populations (Swain and Foote, 1999). Although Sajina *et al.* (2013) reported clear morphological separation between Mandapam populations and those from the northeast and west coasts, the morphometric ranges observed in the present study broadly overlap with the east coast population described in their study. This suggests that the populations along the southeast coast share similar morphological characteristics, while minor variations may occur due to geographic and environmental influences, as well as differences in the size composition of the sampled individuals.

A highly significant positive correlation among the various morphometric characters of *M. cordyla* was observed in the present study. The regression slope values ('b') reflected proportional growth relationships among the morphometric measurements with increasing body size. Among the characters analysed, fork length, standard length, inter-dorsal space, and snout to pelvic length exhibited a very strong positive correlation with total length. In contrast, post-orbital length, snout length and eye diameter showed comparatively lower growth rates, suggesting relatively slower development of these features compared to other morphometric traits.

Sarmin *et al.* (2022) reported a high degree of correlation between standard length and fork length of *M. cordyla* in the Bay of Bengal, Bangladesh. Similar results were also reported from the Northwest coast of India by Jaiswar and Devaraj (1989), who found the highest degree of correlation between standard length and fork length in their study. The present study supports the earlier findings from Bay of Bengal and the Northwest coast of India.

The growth rates of other morphometric characters, such as snout to pelvic, snout to dorsal, snout to anal and body depth, in relation to per unit change in total length, as well as post orbital length, snout length and eye diameter in relation to per unit change in head length, were faster than those of other compared characters for the species. Similar growth patterns have been reported by several researchers in Indian waters, including Poojary and Sundaram (2014) in *Decapterus russelli,* Bhendarkar *et al.* (2014) in *Rastrelliger kanagurta.* Sajana and Bijoy Nandan (2017) in *Alepes djedaba,* Masood *et al.* (2022) in *Alepes vari.*

The present study observed differences in growth patterns among the morphometric characters, which may reflect functional adaptations closely related to the body form and swimming behaviour of *Megalaspis cordyla*. The relatively faster growth of characters such as snout to pelvic, snout to dorsal, snout to anal distance, and body depth with increasing total length may contribute to maintaining body balance and stability during active swimming. In pelagic fishes, the relative positioning of fins and body depth plays an important role in hydrodynamic efficiency and manoeuvrability in open-water environments (Blake, 2004). In contrast, the comparatively slower growth of characters, including post-orbital length, snout length, and eye diameter relative to head length, suggests that these sensory structures develop early and remain proportionally stable as the fish grows. Such growth patterns may help maintain functional efficiency in feeding and visual detection while supporting the streamlined body form characteristic of fast-swimming carangid fishes (Queiroz *et al.*, 2018).

Meristic counts of *M. cordyla* were compared with data from previous studies (Day, 1878; Jaiswar and Devaraj, 1989; Saker *et al.,* 2004; Sarmin *et al.,* 2022), and they are in close agreement with most of the earlier findings presented in Table 6. In the present study, the number of first dorsal spines and the second dorsal spine and rays in *M. cordyla* varied from VII to VIII and I + 10-11,

Table 6. Comparison of meristic characters of *M. cordyla* based on previous studies

Authors	First dorsal spines	Second dorsal spines & rays	Pectoral fin spines & rays	Pelvic fin spines & rays	Anal fin spines & rays	No. of finlets
Day (1878)	6-8	9–11	21	5	8–9	8–10
Weber and Beaufort (1931)	8	10–11	—	5	8–10	7–9
Bal and Rao (1984)	8	10–11	—	—	8–10	7–9
Jaiswar and Devaraj (1989)	8	11–13	19–22	5	9–11	6–9
FAO/SIDP (2000)	8	I+18–20	—	I+5	I+16–17	Dorsal: 7–9| Anal: 8
Saker *et al.* (2004)	8	I+9–14	I+19–20	I+5	I+9–11	5–9
Sajina *et al.* (2013)	8	I+14–18	21–25	I+5	II+I+12–16	Dorsal: 6–8 Anal: 5–7
Habib *et al.* (2017)	8	I+VII; I/11	20–26	I+5	II+I/10	Dorsal: 8 Anal: 6
Hossain *et al.* (2020)	8	VIII; I/18–20	22	I+5	II+I/16–17	Dorsal: 7–9 Anal: 8–10
Sarmin *et al.* (2022)	8	I+14–18	20–26	I+5	II+I+12–16	Dorsal: 6–8 Anal: 5–7
Present study	7-8	I+10–11	10–22	I+4–5	I+6-17	Dorsal: 6–9 Ventral: 6–8

respectively. These findings are largely consistent with previous literature. Day (1878) reported 6-8 first dorsal spines and 9-11 soft rays in the second dorsal fin, while Weber and Beaufort (1931) recorded 8 first dorsal spines and 10-11 soft rays. Bal and Rao (1984) also reported the same findings: 8 first dorsal spines and 11-13 rays, and Saker *et al.* (2004) documented 8 spines and I + 9-14 rays. The FAO/SIDP (2000) described 8 first dorsal spines and I + 18-20 rays. Later studies (Sajina *et al.,* 2013; Habib *et al.,* 2017; Hossain *et al.,* 2020; and Sarmin *et al.,* 2022) provided more detailed accounts of the first and dorsal fin formula, like this: I + 14-18 and I/18-20. In terms of pectoral fin ray count, the present study recorded 10-22 branched rays, aligning closely with the range of 19-26 rays reported in other studies (Jaiswar and Devaraj, 1989; Sarmin *et al.,* 2022). Pelvic fin counts in the present study were I + 4–5, which corresponds with the widely reported value of I + 5 in the previous studies. Anal fin spines and rays ranged from I + 6–17 in the present observation, which falls within the ranges reported in earlier studies: I + 9–11 (Saker *et al.,* 2004) and II + I + 12–16 (Sarmin *et al.,* 2022). The number of finlets in the present study ranged from 6 to 9 dorsally and 6 to 8 ventrally, which closely agrees with earlier studies. Furthermore, the maximum number of meristic counts observed in the present study was generally similar to previous findings, with minor differences noticed in the second dorsal spine rays and anal fin spine rays. These variations could be attributed to various environmental parameters such as temperature, salinity, dissolved oxygen, pH, food availability, and the overall growth condition of the species (Barlow, 1961; Lindsey, 1988). The findings of the present study provide baseline morphometric and meristic data on *M. cordyla* from the Chennai coastal waters. The results contribute to understanding morphological variation in the species and may serve as useful reference data for future comparative studies across different geographical regions and broader investigation of the species.

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Author contributions

Conceptualization: KS; Data curation: KS; Formal analysis: KS; Investigation: KS; Methodology: KS; Software: KS; Writing – original draft: KS; Writing – review and editing: RJ; Writing– review and editing: AT; Supervision: AT; Writing–review and editing: YT; Supervision: KR; Editing: KR.

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

There is no conflict of interest among the authors.

Ethical statement

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Indigenous knowledge used in the gill net fishery practised along the Sindhudurg coast of Maharashtra, India

S. B. Adkar[1], V. H. Nirmale[1]*, S. Y. Metar[1], M. B. Shetkar[1], S. S. Suryawanshi[1] and A. U. Pagarkar[1]

[1]College of Fisheries, Shirgaon- 415 712, Ratnagiri, India.

*Correspondence e-mail: viveknirmale416@gmail.com
*ORCiD: https://orcid.org/0000-0002-2124-5600

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Abstract

The study of indigenous knowledge rooted within fishing communities provides valuable insights for research and sustainable resource management. Indigenous knowledge can provide guidelines for designing fisheries development projects that address priority issues within a fishing community. The present study attempted to explore the indigenous knowledge of fishers engaged in the gillnet fishery. The gillnet fishery is an important traditional fishery practiced in the coastal waters of Sindhudurg district. Data were collected from 75 gillnet fishers using the snowball sampling method and employing semi-structured interviews and non-participant observations. The study documented rich, varied, and potential IKs associated with the management of gillnet fishery, including dimensions of craft and gillnets, hanging coefficient, seasonal yield, species diversity and abundance, depth of operation, preference time for fishing, effects of wind direction, water colour, tides, and lunar cycle on fish catch, etc. Nine types of gillnets across three categories (drift, bottom-set, and trammel) were documented, operated at depths of 5-60 fathoms. Catches were highest between the 4th and 11th day of the lunar cycle, with species-specific seasonal peaks observed across all gillnet types. Wind direction exerted gear-specific effects on catch, and 93.33% of fishers reported intensification of water currents as the primary cyclone indicator. The documented IK provides a scientific basis for integrating traditional fishing practices into the management of small-scale coastal fisheries.

Keywords: *Traditional ecological knowledge, gillnet fishery, small-scale fisheries, Sindhudurg, Maharashtra*

Introduction

Indigenous knowledge (IK) refers to the body of knowledge developed and continuously refined by a community over time. It is based on experience, often practised over centuries, adapted to local culture and environment, and dynamic in nature. Indigenous knowledge has recently become the topic of research in both social and biological sciences, including fisheries (Nirmale *et al.*, 2007). Traditional knowledge is also referred to as indigenous technical knowledge, ethno-ecology, local knowledge, folk knowledge, traditional ecological knowledge, and people's science (Joa *et al.*, 2018). These terms have conceptual and semantic problems. In the present study, the term indigenous knowledge has been used to avoid ambiguity. In fisheries, there is a need to understand and study extensively the indigenous knowledge shared by a particular fisher community (Johannes, 1981). Solutions to fisheries lie outside the sector (Smith, 1981). It is necessary to understand the complexities of a fishing community before recommending and implementing any intervention designed to uplift its standard of living. The generation of indigenous knowledge has been a matter of survival for fishers who use it to overcome their specific localised problems. The knowledge of ecology and fish behaviour (Johannes, 1981), weather and oceanographic conditions, navigation (Worsley, 1971), fishing methods (von Brandt, 1972), vessel design and propulsion, processing, and trade has been effectively used by the fishers to harness local resources sustainably. The gillnet fishery is one of the prominent traditional fisheries practised along the Sindhudurg coast of Maharashtra. It is one of the most ideal fish-catching methods in terms of conservation and stock regulations due to its selective nature (Laxmappa *et al.*, 2014). Fishers operating various types of gillnets in the region likely harbour a vast body of indigenous knowledge encompassing the design, method of fabrication, material used, depth and bottom of operation, timing of the operation, and seasonal abundance of fishery resources, to name a few. Documentation and assessment of traditional knowledge utilized in the gillnet fishery will generate a useful database and focus on the essential research needs. Similarly, the knowledge will help inform assessment and scientific management of the gillnet fishery in the region. According to Saha and Nath (2013), indigenous knowledge is used by local communities to solve problems and sustainably manage resources. Fishers have developed a unique system of knowledge, skills, and innovations related to fishing activities. This knowledge enables them to utilise natural resources sustainably through close interaction with their environment (Gadgil *et al*., 1993). Living in close association with nature, fishers possess a strong indigenous knowledge system (Uskelwar *et al*., 2017) and demonstrate an understanding of marine ecosystems through continuous observation and adaptation (Pukkalla and Rama Mohan, 2021). The findings of the present study further highlight that such knowledge can complement scientific stock assessment and ecosystem-based fisheries management, thereby supporting sustainable utilisation and conservation of marine resources. In the above context, the present study was conducted to study the indigenous knowledge of fishers engaged in gillnet fishery and analyse the rationale behind its use.

Material and methods

The study was conducted in the purposively selected Sindhudurg district of Maharashtra State, as it is one of the maritime districts, where the traditional operation of gillnets forms an important fishery (Fig. 1). The district is endowed with a coastline of 121 kms. The total fisher population of the district is 32017 and is spread across 87 fishing villages; however, catches are landed at only 34 fish landing centres (Anon, 2021-22). A total of 75 respondents from 15 fishing villages in the district were interviewed following the snowball method (Bailey, 1987). The villages selected were located along the northern, middle, and southern regions of the district. Five villages were randomly selected from one block in each region for data collection.

The snowball method is a non-probability sampling technique in which existing study participants refer future participants from among their acquaintances. It is a useful tool for building

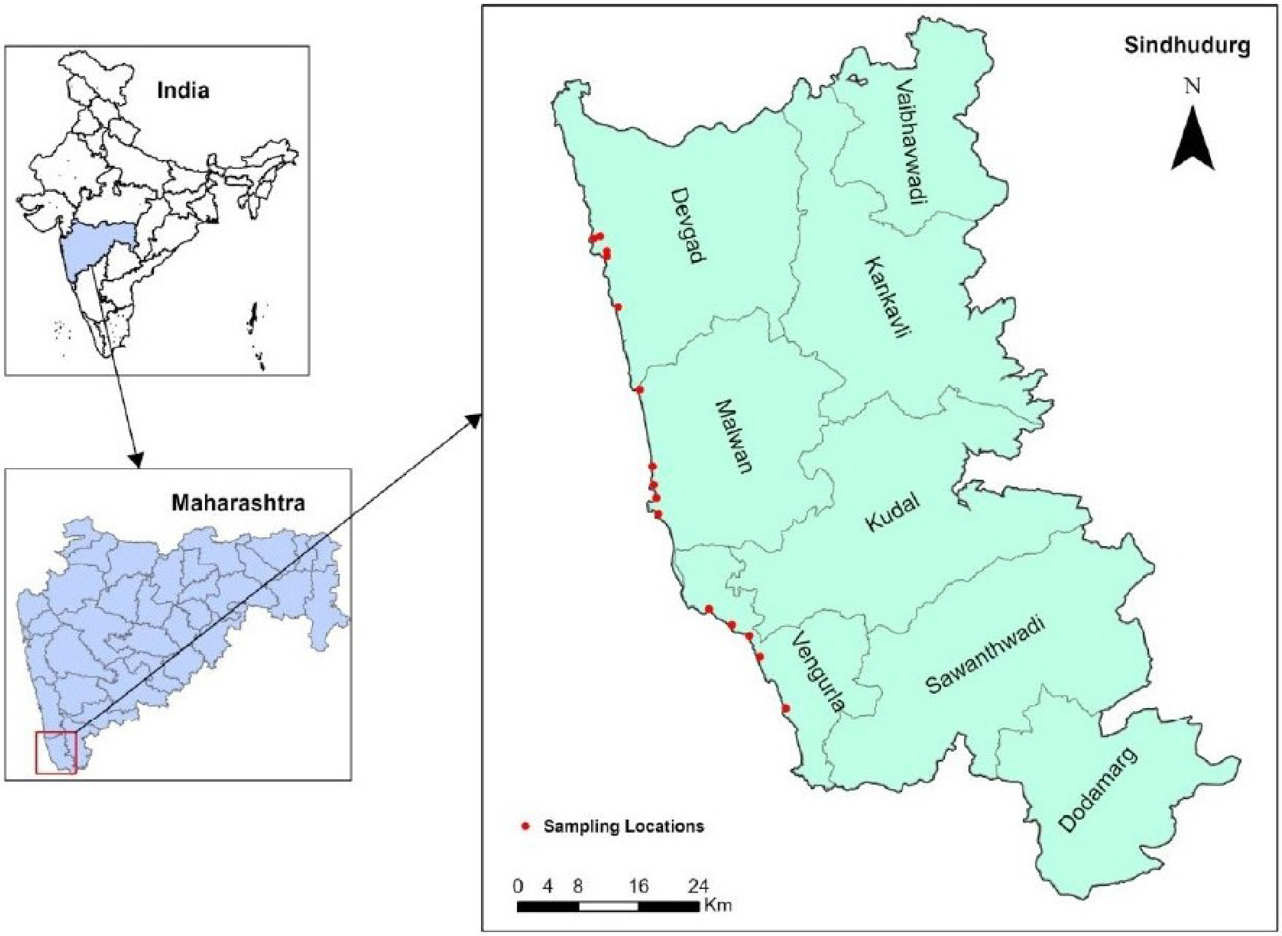

Fig. 1. Study area

a network and increasing the number of participants (Goode and Hatt, 1952). This technique was particularly appropriate for the present study as gillnet fishers in Sindhudurg constitute a small, close-knit community whose members are best identified through peer referral rather than conventional random sampling. The data were collected using a semi-structured interview schedule designed to capture the required information. Responses to a particular question that were frequently mentioned were considered to reflect aspects of indigenous knowledge. Responses were quantified as the percentage of respondents mentioning a given answer; answers reported by 50% or more of respondents were considered to reflect established indigenous knowledge practices of the community. The study findings were further supported by non-participant observation and documentary evidence, thereby providing triangulation of the data collected through interviews. PIC (Prior informed consent) was obtained from the fishers and their names, village names and ages were noted.

Results and discussion

Profile of respondents

The profile characteristics of respondents are given in Table 1. Age-wise distribution of respondents showed that the majority of fishers were above 50 years of age, followed by middle-aged fishers and the younger age group. Veteran fishers were observed to be engaged primarily in the fishery. Most had schooling up to high school. Table 1 indicates that respondents were almost equally represented across small and large family sizes. The majority of respondents possessed substantial fishing experience for over 15 years, reflecting the predominance of highly experienced individuals within the fishery. All respondents were from the *gaabit* community, classified under the constitutional Special Backward Class category.

Dimensions of fishing crafts

For ease of understanding, the results for overall length (OAL), width, depth, and fish hold capacity have been combined for each type of craft and are discussed accordingly (Table 2). The non-mechanised crafts (*pagar/hodi*) with an OAL up to 15-24 ft and width up to 3-5 ft operated 5-10 units of drift gillnets, *viz*., Indian oil-sardine gillnets, fringe scale sardine gillnets, mackerel/false trevally gillnets, and pomfret gillnets. Operation of seerfish gillnets involves the use of mechanised boats known locally as *balyav,* which are operated at a depth of 30-60 fathoms (*vav*). These crafts can carry 25-35 units of sear fish gillnets. The OAL range of these boats is between 32 and 40 ft, with a width between 6 and 17 ft and a depth varying from 4.5 to 10 ft. The motorised fishing vessels are locally known as *paat/ pagar* and are propelled by outboard engines (9.9 hp-25 hp). The OAL of these crafts ranged from 20 to 32 ft, with widths between 4 and 8 ft and depths ranging from 2 to 4 ft. They are used for operating drift gillnets, including mackerel/false trevally gillnets (*tarav/mand*), Indian oil-sardine gillnets (*tarli* chi *tiyani/kandali*), pomfret gillnets (*garpel*), bottom set nets [mackerel/false trevally gillnets (*budav*) and red snapper/grouper gillnets (*budi*)], and trammel nets (*disco*). The dimensions of the fishing crafts concerning OAL, width, depth, and fish hold capacity rely on the suitability of operating the number and type of gillnets in the particular environment, available resources, depth of operation, construction cost, availability of material, and fishers' experience acquired through continuous trial and error.

Materials used for the construction of fishing crafts

The study revealed that approximately 42.67% of fishers in Sindhudurg district used *undal* tree wood (*Calophyllum*

Table 1. Profile characteristics of respondents

No.	Profile characteristics	Categories	Respondents	
			Frequency	Percentage
1	Age	Young (up to 30 years)	5	6.67
		Middle-aged (31 to 50 years)	31	41.33
		Old (more than 50 years)	39	52.00
2	Marital status	Unmarried	11	14.67
		Married	64	85.33
3	Education	Illiterate	-	-
		Read only	-	-
		Read and write	-	-
		Primary school	8	10.67
		High school	50	66.67
		College	17	22.66
4	Size of family	Small (< 4members)	38	50.67
		Large (> 4members)	37	49.33
5	Experience in fishing	up to 15 years	7	9.33
		up to15-30 years	38	50.67
		More than 30 years	30	40.00
6	Community	*Gabit*	75	100.00
		Bhandari	-	-
		Marath	-	-
		Kunbi	-	-

Table 2. Dimensions of fishing crafts

Types of craft	Frequency	Percentage (%)
Non-mechanised crafts (*pagar/hodi*)	15	20
Mechanised crafts (*balyav*)	11	15
Motorised crafts (*paat/pagar*)	37	50

inophyllum) to construct the beams and frames of wooden fishing crafts. *Undal* tree wood is abundant in the Konkan region, as reported by Nirmale *et al.* (2007), and is inherently oily, providing natural water resistance. Additionally, 13.33% equipped their boats with outriggers (*undali*) made from the wood of the *pangera* tree, *Erythrina suberosa,* for stability. The lighter weight of this tree wood facilitates buoyancy. About 12% used a combination of *undal* wood for frames and *aini* tree wood, *Terminalia elliptica,* for frames and beams, respectively. While a few fishers used *aini* and *babul* tree wood, *Acacia arabica,* for decks and beams, respectively. *Aini* tree wood is known for its strength and durability. Babul tree wood is known for its flexibility and can absorb shock without breaking easily (Nirmale *et al.*, 2004).

Types of gillnets, mesh size, depth, and timing of operation

The gillnet fishery has historically been one of the dominant components of marine fisheries in the Sindhudurg district (Naik, 1998). Gillnets target Indian mackerel, false trevally, Indian oil sardine, fringe-scale sardine, pomfret, seer fish, snappers, groupers, and shrimps. A cursory look at Table 3 reveals the gear types, mesh sizes, material composition, and usage patterns of these gillnet types. Gillnets observed in the district can be broadly divided into the following types.

Drift gillnets

Mackerel/false trevally gillnets (tarav/mand): The gillnet used for targeting Indian mackerel/false trevally is locally known as *mand/tarav* with a mesh size of 48-58 mm. It is typically operated at a depth of 10 to 20 fathoms, usually at the surface layer. However, Waghmare *et al.* (2018a, b) previously reported that two separate gillnets with mesh sizes of 51 mm and 47 mm were operated for Indian mackerel and false trevally, respectively. The present study observed fishers employing a single gillnet for both species. This operational shift is driven by fishers' observations that a single mesh size yields high catch proportions for both species, making it a more time-efficient and cost-effective harvesting strategy. The operational depth of gillnets recorded in the present study is up to 20 fathoms, which aligns with the findings of Waghmare *et al.* (2018 a,b). The depth is adjusted according to the availability of the targeted fish species using marked ropes (one fathom apart) known as *Sarki*, attached to the head rope, and a respective buoy placed at a distance of one unit apart (*ghadan*) from each other. Furthermore, the buoyancy and sinking rates were regulated by altering the ratio of floats to sinkers on the head and foot ropes, a technique consistent with methods described by Nirmale (2004). The fishing season for these gillnets typically extends from August to November and is commonly operated from 4-8 a.m. and 5-9 p.m. (*tambus*). The increased catch rates observed during these hours are due to the availability of fish food organisms and the reduced visibility, as reported earlier (Nirmale, 2007).

Indian oil sardine gillnets (*tarli chi tiyani/kandali*) and fringe scale sardine gillnets (*pedvya chi tiyani/kandali*): Indian oil sardine gillnet, locally known as *tarli* chi *tiyani or kandali*, has a mesh size of 36 mm. The net is operated at a depth of 5-15 fathoms (*vav*). Fringe-scale sardine gillnets, referred to as *pedvya chi tiyani* or *kandali*, have a mesh size of 34 mm and are typically operated at depths of 15-20 fathoms. Both types of gillnets are deployed at specific depths and during particular periods of the day in accordance with the availability of target resources. Fishers typically possessed multiple types of gillnets, which are selectively employed to exploit different pelagic fishery resources. Based on observations from preceding days regarding the relative catch composition, fishers preferentially operated Indian

Table 3. Types of gill nets used along the Sindhudurg coast of Maharashtra

Types of nets	Mesh size	Material	Frequency	Percentage (%)
Drift gill nets				
Mackerel/false trevally gill nets (*tarav/mand*)	48–58 mm	Monofilament (*sav*)	44	100
Indian oil-sardine gill nets (*tarli* chi *tiyani/kandali*)	36 mm	Monofilament (*sav*)	17	100
Fringe scale sardine gill nets (*pedvya* chi *tiyani/kandali*)	34 mm	Monofilament (*sav*)	4	100
Mackerel/false trevally gill nets (*bangda/saundala* chi *tiyani/kandali*)	36-48 mm	Monofilament (*sav*)	13	100
Pomfret gill nets (*garpel*)	114-130 mm	Monofilament (*sav*)	26	100
Seer fish gill nets (*aavta/dhangda*)	83-131 mm	Multifilament	17	100
Bottom set gill nets				
Mackerel/false trevally gill nets (*budav*)	48- 50 mm	Monofilament (*sav*)	40	100
Snapper/grouper gill nets (*budi*)	115-150 mm	Monofilament (*sav*)	37	100
Trammel nets				
Disco (inner layer) Outer (tiyana) *vagholdar*	(36) 140 mm	(Monofilament) Nylon	23	100

oil sardine and fringe-scale sardine gillnets during daytime hours. Fishing operations were continued as long as the target resources were available in appreciable quantities.

Mackerel/ false trevally gillnet (*bangda/saundala chi tiyani/ kandali*): *Bangda/saundala* chi *tiyani/kandali* is the local term for mackerel/false trevally gillnet. They have a mesh size of approximately 36-48 mm and are typically operated at a depth of 10-20 fathoms. The depth of operation is consistent with the findings of Waghmare *et al.* (2018a, b) as discussed earlier. Fishing is primarily carried out during early morning and evening hours. Fishers reported higher catches of Indian mackerel and false trevally during these periods, which may be associated with an increased availability of food organisms for both species. Similar observations have been documented by Nirmale *et al.* (2007). Drift gillnets of varying mesh sizes are employed to exploit different size groups of mackerel and false trevally. The selectivity of gillnets is known to be strongly influenced by mesh size, which plays a critical role in determining the size composition of the catch (Sparre and Venema, 1992).

Pomfret gillnets (*garpel*): Pomfret gillnet, locally known as *garpel,* with a mesh size of about 114-130 mm, is generally operated in surface waters at depths of 10-20 fathoms during 4-9 a.m. Deployment of pomfret gillnets at specific depths and times was regulated based on the availability of pomfret resources in the fishing grounds. The fishing season for pomfret extended from September to October. The operational characteristics and seasonal pattern observed in the present study are in agreement with earlier findings reported by Nirmale *et al.* (2007) and Waghmare *et al.* (2018c).

Seer fish gillnets (*aavta/ dhangda*): Seer fish gillnets, locally referred to as *aavta/dhangda* are differentiated by fishers based on mesh size and twine gauge. The mesh size of the units increased with the number of twines and generally ranged from 83 to 131 mm. Gillnet units, fabricated using twine No. 4 and 6, are locally called as *kondashi aavta/dhangda,* whereas those made up of twine No. 8, 10, and 12 are locally known *karal aavta/dhangda*. These gillnets are operated at 30-45 fathoms. The fishing season extends throughout the year; however, fishers report comparatively higher catches during the late monsoon and late summer seasons. A distinguishing feature of these gillnets was the incorporation of multiple units with varying mesh sizes within a single net. Such a configuration was intended to target a wide range of size groups of seer fish occurring at a particular depth. Given the high economic value of seer fish, operational strategies are optimised to enhance catch rates. To increase the catch rates, the depth of operation is adjusted with the help of marked (marked one fathom apart) ropes locally known as *sarki* as discussed earlier. The operational characteristics observed in the present study are consistent with earlier reports by Waghmare *et al.* (2018d) and Nirmale *et al.* (2007).

Bottom set gillnets

Mackerel/ false trevally gillnets (*budav*): Fishers opined that as the fishery progresses, usually after October, mackerel and false trevally move towards the bottom, possibly in response to increasing sea surface temperature (Kizhakudan, 2014). To exploit mackerel and false trevally, which migrate towards the bottom with advancing fishing season, fishers employed bottom-set gillnets (*budav*), having a mesh size that varies from 48-50 mm. These nets are typically operated in bottom layers at depths of 10-20 fathoms during the early morning (5-9 a.m.) and evening (4-8 p.m.), commonly referred to as *tambus.* The Fishing season is from December to May.

Snapper/grouper gillnets (*budi*): Bottom-set gillnets targeting snappers/groupers are locally known as *budi*. The mesh size of these nets ranges from 115-150 mm, and they are operated at depths of 5-20 fathoms. Variations in both mesh size and depth of operation were observed when compared with earlier reports by Waghmare *et al.* (2018c). The observed reduction in mesh size may indicate increased fishing pressure or higher fishing intensity on these resources. These gillnets are operated from 5:30 p.m.-5:30 a.m., depending on the availability of resources.

Trammel nets: Trammel nets, locally known as *disco* nets, are three-layered gillnets primarily used to target shrimps. The outer layer (armour) is made up of larger meshes (140mm) and thicker nylon twine. The outer two layers are locally known as *vagholdar.* The middle layer (lint), locally known as *tiyana*, is made up of smaller meshes (36 mm) and monofilament twine. *Disco* nets are operated from 5-10 a.m., at depths of 5-15 fathoms, usually in the surface layer. Fishing season lasts from August to September. The results are consistent with those of Nirmale *et al.* (2007) regarding mesh size and depth of operation.

Dimensions of different gillnets used by fishers

Gillnets are long, wall-like nets composed of multiple rectangular panels of netting joined together. The ends of the head and foot ropes of two units are tied together. The first end of the first unit and the last end of the last unit are attached to a boat, anchor, or float, depending on the type of gillnets. Irrespective of the type, the dimensions of gillnets employed in a fishery are primarily influenced by fabrication cost, the nature of the fishing ground, and the depth of operation. Fabrication cost increases proportionally with an increase in the dimensions and number of gillnet units. The operation of larger gillnet units over rocky bottoms increases the likelihood of net damage due to entanglement, particularly in the case of drift gillnets and bottom-set gillnets. Similarly, depth of operation also governs gear dimensions, with fishers operating in shallow waters generally employing gillnets of smaller dimensions.

A cursory examination of Table 4 indicates that the number of units operated per gillnet type varied among respondents, with each unit having a standard length and height. Among drift gillnets, mackerel/false trevally gillnets (*tarav/mand*), mackerel/false trevally gillnets (*bangda/saundala chi tiyani/kandali*), Indian oil sardine gillnets (*tarli chi tiyani/kandali*), and pomfret gillnets (*garpel*) were deployed in two-unit categories, indicating flexible strategies based on operational needs. In contrast, seer fish gillnets (*aavta/dhangda*) were uniformly used in larger configurations by all respondents. Bottom set gillnets showed variation as well: mackerel/false trevalley gillnets (*budav*) were operated in two-unit ranges, while snapper/grouper gillnets (*budi*) varied not only in the number of units used but also in the individual unit length. Trammel nets (*disco*), comprising an inner layer (*tiyana*) and an outer layer (*vagholdar*), were generally deployed in fewer units, though a portion of fishers used extended sets. The total length of gillnets depends on the number of units employed during operation and the size of the boat. The dimensions recorded in the present study are largely consistent with earlier reports for mackerel gillnets (Waghmare *et al*., 2018a), pomfret gillnets (Waghmare *et al*., 2018c), bottom-set gillnets (Waghmare *et al*., 2018c), and trammel nets (Kazi *et al*., 2010). However, the length of a single unit of trammel net reported earlier by Waghmare *et al.* (2018d) was slightly higher than that observed in the present study, which may be attributed to differences in the number of fishers surveyed, fishing grounds, and operational practices.

Crew size and wage distribution

Crew size varies from 2 to 6 members, depending on the type and size of gillnets and whether the craft is motorised, non-motorised, or mechanised. Non-motorised crafts were typically operated by 1-3 crew members, motorised boats by 3-5, and mechanised vessels by 4-6 crew members. Fishers using non-motorised crafts did not incur operational costs and shared profits equally among themselves. For motorised boats, fuel costs are first deducted, and the remaining profit is then shared equally among the crew members. Under the *shinari* system, the craft owner owns 50% of the total gillnet units, with the remaining units owned by the crew. Each fisher retains the catch from their own gillnet units. Fifty per cent

Table 4. Dimensions of different gill nets used along the Sindhudurg coast of Maharashtra

Dimensions	Frequency	Percentage
Drift gill nets		
Mackerel/false trevally gill nets (*tarav/mand*)	44	
Length 50 m-100 m and height 5-18 m per unit of gill net		
10-15 pieces (average total length 938 m)	17	38.64
15-20 pieces (average total length 1313 m)	27	61.36
Indian oil-sardine gill nets (*tarli chi tiyani/kandali*)	17	
Length 50 m-100 m and height 5-15 m per unit of gill net		
5-10 pieces (average total length 563 m)	8	47.06
10-15 pieces (average total length 938 m)	9	52.94
Fringe scale sardine gill nets (*pedvya chi tiyani/kandali*)	4	
Length 50 m-100 m and height 5-15 m per unit of gill net		
10-15 pieces (average total length 938 m)	4	100.00
Mackerel/false trevally gill nets (*bangda/saundala chi tiyani/kandali*)	12	
Length 50 m-100 m and height 5-11 m per unit of gill net		
5-10 (average total length 563 m)	9	69.23
10-15 pieces (average total length 938 m)	4	30.77
Pomfret gill nets (*garpel*)	26	
Length 50-100 m and height 5-15 m per unit of gill net		
5-10 pieces (average total length 563 m)	17	65.38
10-15 pieces (average total length 938 m)	9	34.62
Seer fish gill nets (*aavta/dhangda*)	17	
Length 50 m-100 m and height 10-20 m per unit of gill net		
25-35 pieces (average total length 2250 m)	17	100.00
Bottom set gill nets		
Mackerel/false trevally gill nets (*budav*)	40	
Length 50-100 m and height 5-10 m per unit of gill net		
5-10 pieces (average total length 563 m)	16	40.00
10-15 pieces (average total length 938 m)	24	60.00
Snapper/grouper gill nets (*budi*)	37	
Length 50-100 m and height 9 m per unit of gill net		
5-10 pieces (average total length 563 m)	27	72.97
Length 100-150 m and height 9 m per unit of gill net		
5-10 pieces (average total length 938 m)	10	27.03
Trammel gill nets		
Disco	24	
Length 25-50 m and height 5-10 m per unit of gill net		
5-10 pieces (average total length 281 m)	19	79.17
10-15 pieces (average total length 468.75 m)	5	20.83

of the fuel cost is borne by the owner, while the remaining cost is shared among the crew. This system reduces expenses from the owner's perspective while allowing individual fishers to benefit from the catch of their owned units, reflecting an efficient and flexible operational strategy.

Material used for fabrication, floats and sinkers

Natural cotton-based fibre is not used for the fabrication of the gillnets in the present investigation. Therefore, indigenous knowledge in this regard could not be documented. A majority of respondents used monofilament twine (*sav*) for gillnets. Multifilament twine was used by one-fourth of the fishers. For flotation, almost all fishers used *chakate/bhyanda*; circular PVC sponge plastic floats (100-150 mm dia) tied to ropes and attached to the head rope at intervals. This arrangement ensured appropriate tension and positioning of drift gillnets. Fishers preferred float sizes larger than the mesh to prevent net entanglement, and no indigenous materials were employed for floats. All fishers reported using *shevta/sarki* buoys made of thermocol, attached at the end of each gillnet unit using a 3 mm rope (*sarki*) to provide buoyancy and adjust operational depth of drift gillnets. Although indigenous materials were not used for *shevta/sarki*, fishers demonstrated knowledge of Thermocol's buoyancy properties, ensuring effective use of these buoys. Signal buoys (*bavto*) made of bamboo stakes were used by all fishers; attached to one end of each gillnet, except in *budi* (snapper/grouper) gillnets, where buoys were fixed at both ends. Bamboo was preferred for its availability, lightweight and durability; thermocol enhanced buoyancy, while the cement block ensured stability in the water. Sinkers included materials such as cement, stones and lead. Cement rings (*khapre/bhakre*) with diameters of 100-150 mm were most common, while some used smaller cement sinkers (50-80 mm). About 36% of fishers used stones weighing 250-500 g as sinkers for bottom-set gillnets and lead (shisha) for trammel nets. *Nagar*, a moderate-sized stone (about 10 kg), is used to anchor bottom-set gillnets. It is attached to the bottom-set gillnets by a rope, locally known as *haatal*. These results on the use of local materials for sinkers are consistent with earlier observations (Nirmale *et al*., 2007).

Maintaining hanging coefficient (taakawani)

Fishers maintain a hanging coefficient of 0.75 for all drift gillnets and bottom set gillnets (mackerel/false trevally gillnets (*budav*)) and a hanging coefficient of 0.50 for bottom set gillnets (snapper/grouper gillnets (*budi*)). In the case of trammel nets, a hanging coefficient of 0.50 is maintained for the inner layer and 0.70 for the outer layers. Fixing the net to the headline or rope around all or some of its edges at any definite degree of closeness or openness of the meshes is called mounting, and the ratio of stretched netting length to rope length defines the hanging coefficient (Sreekrishna and Shenoy, 2001). A hanging coefficient of 0.75 is maintained by strengthening the first topmost mesh of gillnet webbing with additional multifilament twine (the process is locally known as *faara maarne*). The same process is repeated at a distance of forty meshes apart for the entire length of the gillnet webbing. Afterwards, the head rope is passed through the first row of meshes of the gillnet webbing. The next thirty meshes are stretched; the point on the head rope is marked. The next *faara* (strengthened mesh) is brought to this point and joined to the head rope with another rope (the process locally known as *taak maarne*). The procedure is repeated for meshes that adjoin the foot rope. In this way, a hanging ratio of 0.75 is maintained.

Maintaining a hanging coefficient of 0.50 is done by strengthening the first topmost mesh of the gillnet webbing with additional multifilament twine, as discussed above. The same process is repeated at a distance of forty meshes apart for the entire length of the gillnet webbing. Afterwards, the head rope is passed through the first row of meshes of the gillnets' webbing. The next twenty meshes are stretched, and the point on the head rope is marked. The next *faara* (strengthened mesh) is brought to this point and joined to the head rope with another rope. The procedure is repeated for meshes adjoining the foot rope. In this way, a hanging ratio of 0.50 is maintained. While a hanging coefficient of 0.70 is maintained for the outer layers of trammel nets. This is done by following the above procedure; however, in this case, seven meshes of gillnet webbing are stretched, and the point on the head rope is marked. The next strengthened mesh (*faara*) is brought to this point and joined to the head rope with another piece of rope. The main determinant of the range of lengths of fish caught by gillnets is the hanging coefficient. If the hanging coefficient is low, the net will hang more slack in the water than taut. In this case, it will entangle the fish (King, 1995).

Karslen and Bjarnasson (1986) found that the most suitable hanging ratios lie between 0.5 and 0.8, while Thomas (2001) stated that the typical hanging ratio, ranging from 0.5 to 0.7, is suitable for gillnets.

Seasonal variation in yield to various gillnets

Fishers provided detailed observations on seasonal variation in gillnet yields, reflecting their long-term engagement and intimate knowledge of the fishery. Only major responses

(>50%) considered for analysis are illustrated in Fig. 2. The observations are consistent with prior studies, such as Allison and Okadi (2013), who reported pronounced seasonal variation in gillnet yields in the lower Nun River, Niger Delta, Nigeria. The fishers' empirical knowledge demonstrated a nuanced understanding of temporal changes in fish abundance, which is critical for optimising fishing effort.

Seasonal abundance of different species in various gillnets

Fishers use gillnets as per the availability and abundance of different fish species. To avoid ambiguity and redundancy, the results of the seasonal abundance of different species in various gillnets are discussed together. Gillnets are highly selective gear (King, 1995), allowing smaller individuals to pass through the meshes while larger fish may escape when their head dimensions exceed the gilling capacity of the net (Sparre and Venema, 1992). In the present study, gillnets were used to exploit multiple target species, including Indian mackerel, false trevally, Indian oil sardine, fringe-scale sardine, snappers, groupers, pomfrets, seerfish, and shrimps. However, substantial catches of non-target species with similar size selectivity were also recorded across different types of gillnets. An attempt was therefore made to document the diversity of non-target species captured by gillnets and their seasonal abundance.

Mackerel/false trevally gillnets (*tarav/ mand*) exhibited a high winter abundance of Indian mackerel, false trevally, and *Leiognathus* spp., with croakers peaking in summer. Indian oil sardine and fringe-scale sardine were more abundant in summer, whereas wolf herring peaked in winter; lesser sardine (*Sardinella* spp.) recorded moderate winter catches with lower summer abundance. Indian oil sardine gillnets (*tarli chi tiyani/ kandali*) yielded substantially higher summer catches of oil sardine, false trevally, croakers, and *Leiognathus* spp., and lesser sardine, fringe-scale sardine, and juvenile mackerel maintained moderate catch levels across seasons. Fringe-scale sardine gillnets (*pedvya chi tiyani/ kandali*)

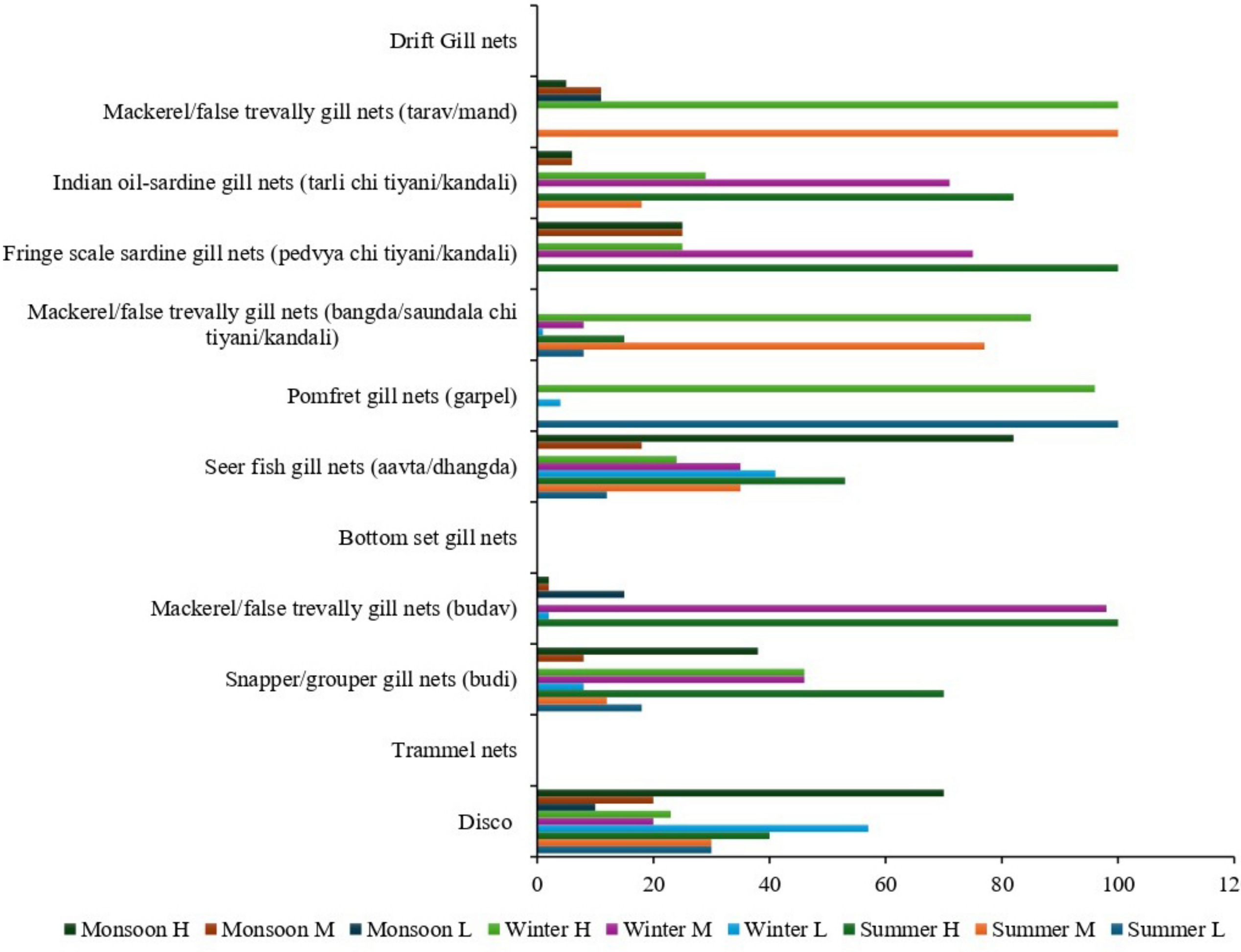

Fig. 2. Seasonal variations in yield to various gillnets

recorded a high summer abundance of fringe-scale sardine and juvenile oil sardine, with *Leiognathus* spp. and lesser sardine peaking in winter; juvenile false trevally remained moderate throughout.

In mackerel/false trevally gillnets (*bangda/saundala chi tiyani/kandali*), winter catches were dominated by Indian mackerel, false trevally, *Leiognathus* spp. and fringe-scale sardine, with croakers more abundant in summer and oil sardine moderate year-round. Pomfret gillnets (*garpel*) yielded substantially higher winter catches of silver pomfret and black pomfret, with markedly reduced catches in summer. Seer fish gillnets (*aavta/dhangda*) demonstrated peak abundance in the late monsoon, moderate occurrence in summer, and minimal catches in winter; associated species, including tunas, elasmobranchs, and dolphin fish, were also most abundant post-monsoon, while black kingfish and catfishes were rarely encountered.

Bottom-set gillnets (*budav*) recorded high summer abundance of Indian mackerel, false trevally, croakers, lesser sardine, and *Leiognathus* spp., with moderate winter occurrence; oil sardine and fringe-scale sardine remained moderate across both seasons. Snapper/grouper gillnets (*budi*) yielded peak grouper catches in late summer, and peak snapper catches in the late monsoon; portunid crabs were most abundant in late summer and moderate in winter. *Acanthopagrus spp*. and eels peaked in summer, while *Siganus* spp., juvenile sharks, and Asian seabass were commonly recorded during the late monsoon and summer; rays and lobsters were frequently reported as incidental catches. Trammel nets (*disco*) exhibited post-monsoon peaks in *Penaeus indicus* and *Metapenaeus affinis* catch rates, whereas eels, catfishes, *Sillago* spp., carangids, and crabs remained consistently low throughout the fishing season. Fishers, by virtue of living in close association with the marine environment and harnessing the natural resources, possess rich knowledge on the ichthyofaunal diversity and its seasonal availability to gillnets.

Table 5. Effects of wind direction on the availability of fish to the gill nets

Effects of wind direction	Responses
Strong winds blowing from the south direction (*bardani*) during June–Aug cease to blow consecutively for forty-two days during monsoon; the yield to gill nets is negatively affected.	23 (30.67)
Winds blowing from the south-east direction (*surmadi vara*) during mid-May to June result in stormy conditions	23 (30.67)
Wind blowing intermittently from southernly (y*etcho varo*) direction after December fetches very little catch to the drift gill net, and on the contrary, fetches high catch to the bottom set gill nets	22 (29.33)
Wind blowing from the north east direction (*dhuri satros varo*) during October results in water becoming turbid and bottom layers becoming relatively colder (*shel lagne*). More yield to drift gill nets is noticed in this situation.	15 (20.00)
Wind blowing from the west direction (entire day) during April to mid-May yields more catch to drift gill nets	10 (13.33)
Winds blowing from the north direction (*uparcho varo*) fetch a high catch to drift gillnets.	6 (8.00)
Wind blowing from an east direction (*matlayi*), then the sea fish move towards the bottom.	5 (7.00)
Wind blows from the south-west (*yet bhaylo varo*) direction, causing less catch in the gill net	4 (5.00)

Fish storage and preservation

A majority of fishers (85.33%) stored their catches in bamboo cane baskets locally known as *topali*, particularly in Sindhudurg district, where storage was generally for a short duration. These baskets are fabricated from locally available bamboo and are preferred due to their light-weight, low cost, and ease of handling. Similar use of bamboo cane baskets has been reported earlier by Nirmale *et al.* (2007). Preservation practices varied among respondents, with about 70% of fishers preserving fish using icing, 26% selling fish fresh, and approximately 4% adopting salt-drying. Icing was the most preferred method as it helps maintain freshness and quality; fish were typically stored in holds or containers with alternating layers of fish and ice in a 1:1 ratio. A small proportion of fishers preserved fish by salt-drying, applying salt at a fish-to-salt ratio of 1:1.7. In this method, fish were washed with seawater, layered alternately with salt for about 48 h, re-salted after turning and subsequently washed and sun-dried on mats made of coconut leaves. During salting, osmotic dehydration removes moisture from the flesh, facilitating effective drying (Nirmale *et al*., 2007; Balachandran, 2001).

Effect of wind direction on fish catch

Multiple views on the effect of wind direction on fish catch and the operation of gillnets have been reported by fishers of Sindhudurg. Table 5 presents indigenous knowledge on the effects of wind direction on fish catch. It represents fishers' perceptions developed through prolonged interaction with the local marine environment. Accordingly, if strong winds from the south direction (*bardani*) during June-August stop blowing consecutively for forty-two days during the monsoon, the yield to gillnets is affected and catches decline during the subsequent year. Winds blowing from the southeast (*surmadi vara*) around mid-May to June cause turbulent conditions, leading fishers to avoid using gillnets. If the wind blows sporadically from the south (*yetcho varo*) after December, the yield to the drift gillnets is decreased, while it is enhanced in the case of the bottom set gillnets. Winds blowing from the northeast (*dhuri satros varo*) in October cause the water to become turbid and the bottom layers significantly cooler (*shel lagne*), resulting in a higher yield in drift gillnets. This effect is especially noticeable in surface water drift gillnets. Similarly, winds blowing throughout the day from the west (*bhaylo varo*) from April to mid-May result in higher yields for drift gillnets. A few fishers believed north winds (*uparcho varo*) improve catch, while east winds (*matlayi*) drive seer fish to deeper waters.

Fishers' perceptions highlight that practical knowledge of fish behaviour and gear efficiency is highly location-, species, season, and gear-specific. Such experiential knowledge, developed through prolonged interaction with the marine environment, plays a critical role in tactical fishing decisions, wherein fishers assess current and recent wind conditions in conjunction with their accumulated experience. Fish movements are strongly influenced by currents and wind direction and intensity, which indirectly affect fish migration patterns. Harden Jones *et al.* (1976) emphasised that currents are closely associated with most fish migrations, with fish often moving in the direction of prevailing currents, particularly under strong flow conditions (Gawn, 1950; Saunders, 1951). Empirical studies examining wind-catch relationships remain limited. For their tactical fishing decisions, fishers observe the present and near past winds and utilise past experiences of the winds and of the relationship between wind and fish availability. A thorough study of currents is necessary for understanding the mechanisms behind fish migrations and movements. There isn't enough scientific research regarding how wind affects fish behaviour. Walden and Schubert (1965) reported poor herring catches off East Anglia during easterly winds, whereas favourable catches were associated with westerly winds along the Danish west coast. Similarly, Jones and Scholes (1980) observed higher cod catches during northerly winds in autumn and winter, while plaice catches in the southern North Sea remained low irrespective of wind direction. They suggested that persistent wind regimes during spawning aggregation periods may establish links between wind directions and catch rates. Although most fishers strongly believe that wind direction influences fish abundance and availability, this locally derived knowledge has rarely been systematically validated through scientific investigation. Given its predominantly coastal and site-specific nature, documenting and scientifically evaluating such knowledge could provide valuable insights for fisheries research and management.

Effects of water colours on the availability of fish

Some fishers noted that clear water yields less catch to all types of gillnets, as noted by 24% of respondents. In contrast, some participants (16%) opined that muddy water results in higher catches in all gillnet types, while 9.33% indicated that brown and bluish water conditions yield moderate to relatively higher catches. Fishers reported that anchovies, Indian mackerel, false trevally, croakers, and lobsters are mostly caught in bottom set gillnets [mackerel/ false trevally gillnets (*budav*)] in muddy water; trammel nets (*disco*) in muddy water yield more shrimp. In muddy water, croakers, snappers, groupers, lobsters, crabs, and pomfrets are caught more in bottom set gillnets, snapper/grouper gillnets (*budi*), and drift gillnets [mackerel/false trevally gillnets (*tarav/mand*)] respectively. In brown water, higher catches of sardines, croakers, and catfishes using drift gillnets and bottom set gillnets are reported.

Through experience, fishers have gained local ecological knowledge on the relationship between the colour of the water and the availability of fish. Muddy water is characterised by high concentrations of suspended particles and planktonic organisms, particularly diatoms and zooplankton. As zooplankton constitutes the primary food source for juvenile stages and small pelagic fishes, its abundance may explain the increased availability of fish in turbid waters. Moreover, gillnets are considered more efficient under turbid conditions, possibly due to reduced visual efficiency of sight-feeding fishes with increasing turbidity. Conversely, the occurrence of low fish abundance in clear water was attributed to the limited availability of food organisms. Murphy (1959) reported that surface gillnet catches of albacore (*Thunnus alalunga*) were significantly influenced by water transparency. Similarly, water colour and plankton content have been identified as useful indicators of surface water types (Macumo, 1957). Fishers also noted that occasional illumination of water due to fluorescent bacteria, particularly during new moon phases, enhances fish visibility, enabling them to detect and avoid gillnets, thereby reducing catch efficiency.

Effect of tides on fish catch and nets

The gravitational forces of the moon and the sun regulate oceanic tides, with the moon exerting a dominant influence due to its proximity to the Earth. About 16% of participants noted higher catches during the transition period (*modvni*), in seerfish gillnets and snapper/grouper gillnets. 9.33% of respondents opined that the probability of drift and bottom-set gillnets getting stuck in rocky bottom increases during high tide, and fish migrate opposite to the water current. Similarly, about 5.33% believed that during low tide, due to the water current, there is a possibility of getting disturbed bottom set gillnets, while high tide yields a moderate catch. Gillnets primarily capture actively swimming fish that encounter the net panels, and the increased current velocity during high tides may enhance fish movement and contact with the gear, thereby influencing catch rates (Nirmale *et al.*, 2007; Uskelwar *et al.*, 2017).

Effect of the lunar cycle on fish catch

Most fishers reported reduced catches in both drift gillnets (mackerel/false trevally: *tarav/mand*; seer fish: *aavta/dhangda*) and bottom-set gillnets (mackerel/false trevally: *budav*; snapper/grouper: *budi*) during new and full moon phases. These periods coincide with spring tides, which occur twice monthly when the Earth, Moon, and Sun are nearly aligned, generating strong tidal currents. Fishers indicated that the intensified currents during spring tides disturb gillnets, particularly those set in rocky areas, increasing the likelihood of net displacement and entanglement with substratum. Further, fishers reported that the period between the 4th day (*chaturthi*) to 11th day (*ekadashi*) of the lunar cycle yields high catch to drift gillnets [mackerel/false trevally gillnets (*tarav/mand*), seer fish gillnets (*aavta/dhangda*)], bottom set gillnets [mackerel/false trevally gillnets (*budav*) and snapper/grouper gillnets (*budi*)]. Fishers perceived that relatively calmer waters during this period allowed gillnets to remain properly positioned, resulting in increased catching efficiency. Similar influences of the lunar cycle on fishing efficiency have been documented earlier for dol nets, longlines, gillnets, bivalve fisheries, and stake nets, indicating a consistent relationship between lunar-driven tidal dynamics and fishing success (Nirmale *et al*., 2007; Nirmale *et al*., 2012; Gangan *et al*., 2014; Uskelwar *et al*., 2017).

Indicators of identification of resource availability in particular locations

Approximately 49% of fishers identify the availability of fishery by movement and shape of the fish shoals, including the swift movement of oil sardine shoals characterised by foamy appearance (*fes*), the rapid caudal fin movements of fringe scale sardine shoals, and Indian mackerel oval-shaped shoals with heads of individual fishes moving over the water surface at the gill region. Pelagic fishes are generally known to move in shoals (Bal and Rao, 1984; Ashaletha and Sheela, 2008; Salim and Antony, 2013). Drift gillnet operations are typically initiated concurrently with the appearance of such shoals, with nets deployed in a transverse or slightly curved orientation to maximise capture efficiency.

Indicators of cyclones/storms

The majority of respondents (93.33%) reported that an increase in water current intensity is an indicator of an imminent storm within a few hours. Additionally, 89.33% observed jerks while hauling nets before cyclonic events, and 82.67% reported that wind blowing from the southern direction served as a reliable indicator. Fishers also reported other signs, including seawater remaining unusually calm, locally referred to as *'sushi marne'* (68%), mud entering water in the form of nodules locally known as *malaki* (60%), and nearshore waters slowly becoming turbid (49.33%). A few other indicators include unusual waves appearing at the surface in relatively deeper waters, locally known as a *lambar* (34.67%), the seabed making noise (26.67%), clouds appearing close to the horizon, locally called *mendhra or kupe* (18.67%), and distant rocks and mountains appear unexpectedly closer than they actually are. These observations are consistent with earlier reports by Nirmale *et al.* (2007), Santha *et al.* (2014), and Johnston (2015).

Fishers further noted that aquatic animals exhibit unusual behaviour preceding storms. The sudden disappearance of fish and surfacing of sea snakes (*mharuche*) were commonly reported, consistent with observations by Nirmale *et al.* (2007). Laevastu (1961) emphasised that fishers' experience allows them to recognise storm impacts on fish occurrence and migration, with storms limiting shoreward distribution (Robins, 1957). Similarly, Bernard (1973) observed porpoises leaving areas hours before storms, while Jones and Scholes (1980) reported herring and pilchards off Cornwall migrating to deeper waters at least ten hours before storm impact. Laevastu (1993) suggested that such pre-storm fish responses may result from internal wave activity or current changes induced by shifting surface pressure systems.

IK in Maharashtra's coastal fisheries has been previously documented by Nirmale *et al.* (2007) among fishers of Mumbai, encompassing craft construction, fish preservation, and tidal and storm indicators across multiple gear types, and by Uskelwar *et al.* (2017) in the estuarine stake net (*wan*) fishery of Ratnagiri, a fixed tidal gear. The present study extends this knowledge to the Sindhudurg coast, where gillnet fisheries, comprising drift, bottom-set, and trammel nets, targeting diverse pelagic and demersal assemblages are practised exclusively by the *gabit* fishing community, representing a distinct socio-cultural and operational context. Several indigenous practices documented in this study, including depth regulation using marked ropes (*sarki*) and buoys (*ghadan*), the *shinari* profit-sharing system, gear-specific wind direction indicators, and adaptive gear consolidation strategies, have not been previously reported from the Maharashtra coast. The IK documented in this study is consistent with established scientific understanding of fish behaviour and environmental variability. Higher catch rates during early morning and evening hours correspond to diel activity patterns and reduced gear visibility, while increased catches in turbid waters reflect reduced visual detection of gillnets. Seasonal variations in fish availability reported by fishers align with known migration and distribution patterns. Such knowledge can complement conventional fisheries science, particularly in data-limited small-scale fisheries, by providing fine-scale insights into species seasonality, fishing grounds, and gear selectivity.

Conclusion

The present study has generated an important database related to the use of indigenous knowledge in the gillnet fishery in the district. Knowledge regarding the selection of fishing grounds, gillnet operations, species composition and seasonal abundance, the influence of lunar cycles on fisheries, and resource allocation will help in designing appropriate management interventions. The study documented nine types of gillnets across drift, bottom-set, and trammel categories operated at depths of 5-60 fathoms, with species-specific seasonal abundance and peak catches between the 4th and 11th day of the lunar cycle. Scientific studies on catch composition and seasonal abundance in the gillnet fishery will help devise the optimum mesh size for the gillnet. Further, when combined thoughtfully with modern, science-based fishing methods, indigenous knowledge can significantly enhance fisheries management. Thus, integrating indigenous and modern approaches is essential for the holistic development of Indian marine capture fisheries.

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Author contributions

Conceptualization: SBA, VHN; Methodology: SBA, VHN; Data Collection: SBA, MBS, SSS; Data Analysis: SBA, MBS, SSS; Writing Original Draft: SBA, VHN, SYM; Writing Review and Editing: VHN, SYM, MBS, SSS; Supervision: AUP

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of samples/ protected environments.

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Taxonomy of marine nematode assemblages along the central west coast of India

G. Sivaleela[1]*, S. Balakrishnan[2] and R. Florence Suganya[1]
[1]Marine Biology Regional Centre, Zoological Survey of India, Chennai – 600 028, India.
[2]Marine Aquarium Regional Centre, Zoological Survey of India, Digha, West Bengal – 721 428, India.

*Correspondence e-mail: sivaleelazsi1@gmail.com
ORCiD: https://orcid.org/0000-0001-5081-1942

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Short Communication

Abstract

The central west coast of India supports a rich diversity of meiofaunal communities. The present study focuses on documenting the most abundant meiofaunal taxa, the free-living nematodes, along the Malvan, Ratnagiri, and Goa coast. Sediment samples were collected from 22 intertidal sites using a hand corer. Post preservation and decantation, 240 free-living meiofaunal nematodes were sorted, and a total of 98 nematode species were identified, representing 6 orders, 20 families, and 53 genera. The survey yielded 1 new record for the Indian subcontinent and 5 new distributional records for the west coast of India. The family Xyalidae, with 26 species, was dominant, followed by the family Chromadoridae with 11 species. These findings contribute valuable baseline data for future meiofaunal studies along the Indian coastline.

Keywords: *Central west coast, meiofauna, nematode assemblages, new distributional records*

Introduction

Meiofauna are microscopic, sediment-dwelling organisms. In estuarine, coastal, and deep-sea habitats, nematodes are the most dominant meiofaunal group, often comprising 60–90% of individuals (Sautya *et al*., 2021; Cavalcanti *et al*., 2023; Chertoprud and Novichkova, 2023). These free-living nematodes play a vital role in maintaining marine sediment ecosystem health through microbioturbation, which enhances oxygen penetration and nutrient redistribution. Their feeding activity breaks down organic matter, and moderate grazing on bacteria prevents microbial overgrowth, sustaining a dynamic microbial community. Nematodes also excrete nitrogen-rich compounds that stimulate microbial growth (Hubas *et al*., 2010). As trophic intermediaries, they connect microbial assemblages to higher trophic levels, facilitating energy transfer within benthic food webs (Schratzberger and Ingels, 2018). These functions highlight their crucial ecological role in benthic environments.

In addition to their ecological roles, free-living marine nematodes are effective bioindicators of environmental change due to their sensitivity, abundance, and habitat specificity. Nematode communities show rapid shifts in response to pollution, oxygen depletion, eutrophication, and habitat disturbance (Ridall and Ingels, 2021). Their localized responses, short life cycles, and functional diversity make them ideal for assessing ecosystem health. However, despite their significance, free-living nematodes remain understudied due to their microscopic size and preservation challenges.

The west-central coast of India, including Maharashtra, Goa, and Karnataka, is a biodiverse region with critical ecosystems such as estuaries, mangroves, and sandy beaches that sustain fisheries and local livelihoods (Prasanna Kumar *et al*., 2015). Ansari *et al.* (1980) reported that nematodes and foraminiferans made up 60–80% of sub-littoral meiobenthos off Goa. Bhadury *et al.* (2015) identified 33 species of free-living nematodes from 20 genera and 13 families along the central west coast of India, noting habitat-specific distributions of key families. Despite these contributions, a comprehensive checklist of free-living nematodes for the region has yet to be compiled. This study aims to fill this gap by producing a detailed checklist of nematodes from 22 ecologically diverse sites along the central west coast of India, contributing to a better understanding of regional nematode biodiversity and providing a foundation for future ecological and conservation research.

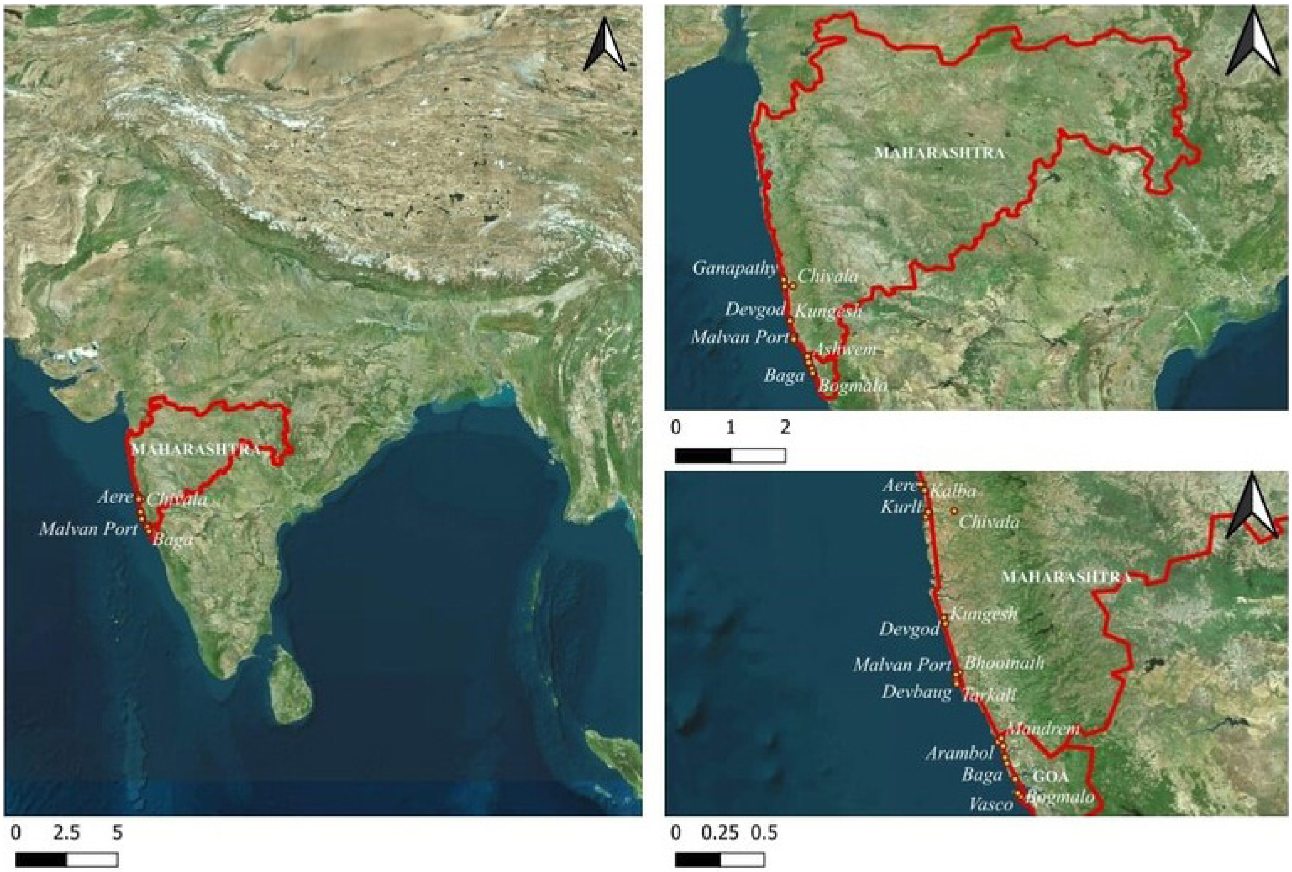

Fig. 1. Sampling sites

Material and methods

Sediment samples were collected using a hand corer of 5cm length and 3 cm diameter from 22 intertidal sites (Table 1) along the central west coast of India. From each site, 3 to 5 sediment samples at a distance of 100 meters were taken. The sampling was carried out during the monsoon and post-monsoon seasons. Mgcl$_2$ was immediately added to narcotise the animal, then the samples were preserved in 5% formalin. The extraction of meiofauna from preserved samples for quantitative analysis can be done by the decantation method, in which the sediments are sieved through an outer sieve made of stainless steel with a mesh size of 1000 μm (1 mm) and an inner sieve made of brass with a mesh size of 63 μm, and the residues were examined. The decanted sediment sample was then observed under a petri dish, and the nematodes were handpicked using a fine needle under a stereomicroscope. Handpicked meiofauna were transferred to pure glycerin and mounted on a microscopic glass slide for taxonomic identification under a high-resolution microscope. Identifications were made based on the descriptions and pictorial keys of Warwick *et al.*, 1998.

Results

A total of 240 free-living marine nematode specimens were collected from the study area, and the specimens belong to 6 orders, 20 families, 53 genera, and 98 species. The list of recorded species is given in Table 1. The 20 families were ranked in decreasing order based on the number of species collected, with Xyalidae being the most dominant, followed by Chromadoridae, Comesomatidae, Desmodoridae, Oncholaimidae, Microlaimidae, Camacolaimidae, Leptolaimidae, Selachinematidae, Monoposthiidae, Axonolaimidae, Ethmolaimidae, Draconematidae, Richtersiidae, Thoracostomopsidae, Enchelidiidae, Linhomoeidae, Aegialoalaimidae and Ceramonematidae.

Table 1. Checklist of free-living meiofaunal nematodes from the Central West Coast of India

No.	Order, family and species
	Order: Araeolaimida
	Family: Axonolaimidae
1	*Axonolaimus helgolandicus* Lorenzen, 1971
2	*Axonolaimus hexapilus* Wieser and Hopper, 1967
	Family: Comesomatidae

No.	Order, family and species
3	*Dorylaimopsis punctata* Ditlevsen, 1918
4	*Paracomesoma dubium* (Filipjev, 1918) Schuurmans Stekhoven, 1950
5	*Sabatieria celtica* Southern, 1914
6	*Sabatieria elongata* Jayasree and Warwick, 1977
7	*Sabatieria longispinosa* Lorenzen, 1971
8	*Sabatieria ornata* (Ditlevsen, 1918) Filipjev, 1922
9	*Sabatieria predatrix* de Man, 1907
10	*Sabatieria pulchra* (Schneider, 1906) Riemann, 1970
11	*Sabatieria punctate* (kreis, 1924)
	Order: Chromadorida
	Family: Chromadoridae
12	*Acantholaimus polydentatus* Gerlach, 1951
13	*Actinonema pachydermatum* Cobb, 1920
14	*Chromadora macrolaima* de Man, 1889
15	*Chromadora nudicapitata* Bastian, 1865
16	*Chromadorella duopapillata* Platt 1973
17	*Chromadorina granulopigmentata* (Wieser, 1951) Wieser, 1954
18	*Dichromadora cucullata* Lorenzen, 1973
19	*Dichromadora geophila* (de Man, 1876) Kreis, 1929
20	*Hypodontolaimus colesi* Inglis, 1962
21	*Prochromadora orleji* (de Man, 1880) Filipjev, 1922
22	*Spilophorella candida* Gerlach, 1951
	Family: Selachinematidae
23	*Choanolaimus psammophilus* de Man, 1880
24	*Choniolaimus papillatus* Ditlevsen 1918
25	*Gammanema conicauda* Gerlach, 1953 – Fig. 2 C
	Family: Ethmolaimidae
26	*Comesa interrupta* (Warwick, 1971)
	Family: Cyatholaimidae
27	*Cyatholaimus gracilis* (Eberth, 1863) Bastian, 1865
28	*Paracanthonchus heterodontus* (Schulz, 1932) Vincx *et al.*, 1982
29	*Paracanthonchus longicaudatus* Warwick, 1971
30	*Paracanthonchus multitubifer* Timm, 1961
31	*Paracanthonchus spectabilis* Allgen, 1931
32	*Paracanthonchus thaumasius* (Schulz, 1932) Vincx *et al.*, 1982
33	*Paracyatholaimus occultus* Gerlach, 1956 – Fig. 3 A and B
34	*Paracyatholaimus pentodon* Riemann, 1966
35	*Paralongicyatholaimus* minutus Warwick, 1971
36	*Pomponema tesselatum* Wieser and Hopper, 1961
	Order: Desmodorida
	Family: Desmodoridae
37	*Chromadoropsis vivipara* (de Man, 1907) Allgen, 1928
38	*Chromaspirina multipapillata* Jayasree and Warwick, 1977
39	*Chromaspirina parapontica* Luc and De Coninck, 1959 – Fig. 2 B
40	*Desmodora scaldensis* de Man, 1889
41	*Desmodora communis* (Bütschli, 1874) De Man, 1889
42	*Desmodorella sanguinea* (Southern, 1914) Verschelde *et al.*, 1998
43	*Metachromadora suecica* (Allgén, 1929) Schulz, 1938
44	*Molgolaimus allgeni* (Gerlach, 1950) Jensen, 1978
	Family: Draconematidae
45	*Draconema claparedii* (Metschnikoff, 1867) Filipjev, 1918 – Fig. 2 A
46	*Paradraconema spinosum* (Southern, 1914) Allen and Noffsinger, 1978
	Family: Microlaimidae
47	*Microlaimus acinaces* Platt and Warwick, 1973
48	*Microlaimus marinus* (Schulz, 1932) Schuurmans Stekhoven and De Coninck, 1933
49	*Microlaimus monstrosus* Gerlach, 1953
50	*Microlaimus parahonestus* Gerlach, 1950
	Family: Monoposthiidae
51	*Monoposthia costata* (Bastian, 1865) de Man, 1889
52	*Monoposthia mirabilis* Schulz, 1932
53	*Nudora bipapillata* Platt, 1973
	Family: Richtersiidae
54	*Richtersia inaequalis* Riemann, 1966
	Order: Enoplida
	Family: Oncholaimidae
55	*Adoncholaimus panicus* Cobb, 1930
56	*Metoncholaimus albidus* (Bastian, 1865) Filipjev, 1918 – Fig. 2 F
57	*Oncholaimus dujardinii* De Man, 1876
58	*Oncholaimus oxyuris* Ditlevsen, 1911
59	*Viscosia cobbi* Filipjev, 1918 Stekhoven 1954
60	*Viscosia langrunensis* (de Man, 1890)
61	*Viscosia viscosa* (Bastian, 1865) de Man, 1890
	Family: Thoracostomopsidae
62	*Mesacanthion hirsutum* Gerlach, 1953
	Family: Enchelidiidae
63	*Pareurystomina acuminata* (de Man 1889) Gerlach, 1952
	Order: Monhysterida
	Family: Xyalidae
64	*Daptonema hirsutum* (Vitiello, 1967) Lorenzen, 1977
65	*Daptonema invagiferoum* (Platt, 1973) Lorenzen, 1977
66	*Daptonema normandicum* (de Man, 1890) Lorenzen, 1977
67	*Daptonema oxycerca* (de Man, 1888) Lorenzen, 1977
68	*Daptonema psammoides* (Warwick, 1970) Tchesonov, 1990
69	*Daptonema setifer* (Gerlach, 1952) Lorenzen, 1977
70	*Daptonema setosum* (Bütschli, 1874) Lorenzen, 1977
71	*Daptonema tenuispiculum* (Ditlevsen, 1918) Lorenzen, 1977
72	*Daptonema vicinum* (Riemann, 1966) Lorenzen, 1977
73	*Gonionchus cumbraensis* Benwell, 1981

No.	Order, family and species
74	*Gonionchus longicaudatus* (Ward, 1972) Lorenzen, 1977
75	*Metadesmolaimus aduncus* Lorenzen, 1972
76	*Paramonohystera buetschlii* (Bresslau and Schuurmans Stekhoven in Schuurmans Stekhoven, 1935)
77	*Promonhystera albigensis* Riemann, 1966
78	*Rhynchonema brevituba* Gerlach, 1953 – Fig. 2 E
79	*Rhynchonema hirsutum* Hopper, 1961
80	*Theristus acer* Bastian, 1865 – Fig. 3. G and H
81	*Theristus bastiani* Gerlach and Riemann, 1973
82	*Theristus complexus* Jayasree and Warwick, 1977
83	*Theristus denticulatus* Warwick, 1970
84	*Theristus ensifer* Gerlach, 1951
85	*Theristus flevensis* Schuurmans Stekhoven, 1935
86	*Theristus interstitialis* Warwick, 1970
87	*Theristus longus* Platt, 1973 – Fig. 2 D
88	*Theristus otoplanobius* Gerlach, 1951
89	*Xyala striata* Cobb, 1920 – Fig. 3. C and D
	Family: Linhomoeidae
90	*Desmolaimus zeelandicus* de Man, 1880
	Order: Plectida
	Family: Aegialoalaimidae
91	*Aegialoalaimus elegans* de Man, 1907
	Family: Ceramonematidae
92	*Ceramonema reticulatum* Chitwood, 1936 – Fig. 3 I and J
	Family: Camacolaimidae
93	*Deontolaimus longicauda* (de Man, 1922) Holovachov and Boström, 2015
94	*Deontolaimus tardus* (de Man, 1889) Holovachov and Boström, 2015
95	*Stephanolaimus elegans* Ditlevsen, 1918
	Family: Leptolaimidae
96	*Leptolaimus ampullaceus* Warwick, 1970
97	*Leptolaimus papilliger* de Man, 1876
98	*Leptolaimus pellucidus* (Southern, 1914) Holovachov and Boström, 2013

New records and new distributional records

Draconema claparedii (Metschnikoff, 1867) Filipjev, 1918

The head is oval-shaped and distinctly separated from the trunk, with the mouth situated at the anterior end. It is followed by a body that is swollen at the midsection and gradually tapers to terminate in a pointed tail. The genital and anal openings are positioned ventrally. Just anterior to the anus, a double row of approximately 15 cylindrical rods is present on each side. A notable feature of this species is the presence of peculiar hooks located on the anterior region of the head, which appear to be diagnostic. The entire cuticle exhibits fine striations, with coarser striations restricted to the central portion of the head and occasionally observed on the tail.

Order: Desmodorida De Coninck, 1965
Super Family: Desmodoroidea Filipjev, 1922
Family: Draconematidae Filipjev, 1918
Genus: *Draconema* Cobb, 1913
Original name: *Chaetosoma claparedii* Metschnikoff, 1867
Materials Examined: 2exs; Reg. No. N.461. Sta: Chivala. Date: 7.11.2017.
Distribution: Uppanar estuary, Tamil Nadu. (Victor Raj *et al,* 2019).
Elsewhere: Mediterranean Sea and North Atlantic Ocean.
Remarks: This is a new distributional record for the West Coast of India.

Chromaspirina parapontica Luc and De Coninck, 1959

The body is elongated and robust, slightly tapering at both the anterior and posterior ends. The cuticle is relatively thin and exhibits very fine annulations, restricted to the anterior portion of the body. Fine striations begin near the anterior margin of the amphidial region. Eight longitudinal rows of short setae are distributed along the entire body. Amphids are spiral in structure. The head is smoothly rounded and lacks a basal constriction. The lip region consists of six lips, bearing six internal labial papillae, six external labial setae, and four cephalic setae. The oesophagus is slightly swollen anteriorly. The tail is short, stout, and conically tapering.

Order: Desmodorida De Coninck, 1965
Super Family: Desmodoroidea Filipjev, 1922
Family: Desmodoridae Filipjev, 1922
Genus: *Chromaspirina* Filipjev, 1918
Materials Examined: 2 Exs. Reg.No.N.583. Sta: Baga. Date:24.6.18.
Distribution: India. Uppur, Tamilnadu (Sivaleela, 2012)
Elsewhere: North Sea & North Atlantic Ocean.
Remarks: This is new distributional record to West Coast of India.

Gammanema conicauda Gerlach, 1953

The body is elongated and cylindrical, tapering anteriorly, with its maximum width located mid-body. Transverse rows of fine punctations mark the cuticle. The broad oral cavity is encircled by 12 slender, hair-like structures that appear interconnected by a membranous ring. Surrounding this is a secondary ring composed of six prominent labial bristles. The oesophagus is cylindrical along most of its length but is distinctly enlarged anteriorly to form a well- developed pharyngeal bulb. The short, conical tail houses visible caudal glands.

Fig. 2 A) *Draconema claparedii* (Metschnikoff, 1867) Filipjev, 1918*;* B) *Chromaspirina parapontica* Luc and De Coninck, 1959; C) *Gammanema conicauda* Gerlach, 1953; D) *Theristus longus* Platt, 1973; E) *Rhynchonema brevituba* Gerlach, 1953*;* F) *Metoncholaimus albidus* (Bastian, 1865) Filipjev, 1918

Order: Chromadorida Chitwood, 1933
Super Family: Chromadoroidea Filipjev, 1917
Family: Selachinematidae Cobb, 1915
Genus: *Gammanema* Cobb, 1920

Material Examined: 5 ex. Reg.No.N.571 & N.465. Sta. Ganapathypule and Devgod Date: 8.11.17; 21.6.18.
Distribution: Uppanar Tamilnadu (Victorraj *et al* 2019).
Elsewhere: Belgium, North Atlantic Ocean and North Sea.

Remarks: This is a new distributional record for West Coast of India.

Theristus longus Platt, 1973

Body slender with distinct cephalic and somatic setae distributed throughout. Cephalic setae comprise six longer and four shorter ones. Somatic setae are fine and present along the body. Amphids are situated anteriorly and relatively small in diameter. The tail is elongated. Spicules are strongly cephalate proximally, while the gubernaculum is lightly cuticularized with two distal hooks and lacking an apophysis. The vulva is positioned slightly beyond the mid-body region.

Order: Monhysterida Filipjev, 1929
Super Family: Sphaerolaimoidea Filipjev, 1918
Family: Xyalidae Chitwood, 1951
Genus: *Theristus* Bastian, 1865
Material Examined: 1ex. Reg.No.N.596. Sta: Aereware. Date: 25.12.18
Distribution: India: Continental shelf of the southwestern Bay of Bengal (Ansari *et al*., 2012);
Sundarban mangroves (Ansari and Bhadury, 2017)
Elsewhere: Strangford Lough, North East Ireland.
Remarks: New distribution to the west coast of India

Rhynchonema brevituba Gerlach, 1953

The body exhibits a characteristic tapering anteriorly, commencing just posterior to the oesophageal region. The cuticle is distinctly annulated with prominent, hoop-like rings, each slightly exceeding 2 μm in width. Relatively long, slender somatic setae are distributed along the body. Anteriorly, preceding the cephalic setae, the lip region is distinctly swollen and spherical. The tail shows minimal tapering along the initial two-thirds of its length, followed by a rapid narrowing into a small, slender, and unringed terminal tubule.

Order: Monhysterida Filipjev, 1929
Super Family: Sphaerolaimoidea Filipjev, 1918
Family: Xyalidae Chitwood, 1951
Genus: *Rhynchonema* Cobb, 1920
Material Examined: 1ex. Reg.No.N.643. Sta: Baga. Date: 28.12.2018.
Distribution: Europe island, North Sea, Australia, Indo West Pacific & Mediterranean Sea.
Remarks: This species is a new record for India

Metoncholaimus albidus (Bastian, 1865) Filipjev, 1918

The body is elongated and whitish, tapering anteriorly but more prominently towards the posterior end. The head is truncate and bears a circlet of four short, stout setae, along with a few smaller setae scattered over the anterior region of the body. Amphids level with dorsal tooth and the buccal cavity is large with three teeth. The integument exhibits distinct longitudinal markings. The oesophagus is short and slightly expands posteriorly.

Order: Enoplida Filipjev, 1929
Super Family: Oncholaimoidea Filipjev, 1916
Family: Oncholaimidae Filipjev, 1916
Genus: *Metoncholaimus* Filipjev, 1918
Original name: *Oncholaimus albidus* Bastian, 1865
Material Examined: Reg.No.N.557, Sta. Arambol. Date.24.6.18.
Distribution: Pudukudi, Palk Bay. (Sivaleela, 2016)
Elsewhere: Plymouth, Isles of Scilly
Remarks: This is the new distributional record from the West Coast of India.

Discussion

The current study reports one new record for India; *Rhynchonema brevituba* Gerlach, 1953, and five new distributional records to the west coast of India; *Draconema claparedii* (Metschnikoff, 1867) Filipjev, 1918, *Chromaspirina parapontica* Luc and De Coninck, 1959, *Gammanema conicauda* Gerlach, 1953, *Theristus longus* Platt, 1973, and *Metoncholaimus albidus* (Bastian, 1865) Filipjev, 1918. These additions expand the known biogeographic range of these taxa and emphasize the underexplored diversity of meiofauna in the west coast region.

Comparative morphological analysis with Indian congeners reveals notable interspecific variations across the recorded taxa. *Metoncholaimus albidus* is the only species of its genus reported from India, precluding regional congeneric comparison. Among the studied genera, *Theristus* has the highest number of congeners in India, with species exhibiting subtle variations in cuticle and Buccal cavity morphology; *T.longus* is distinguished by its exceptionally long tail and shows close affinity to *T. pertenuis* (Lorenzen, 1973), differing mainly in spicule structure and amphid size. The genus *Gammanema*, represented by five Indian species, displays the greatest variation in the head region and buccal cavity, with *G.conicauda* showing partial resemblance to *G. magnum*. *Chromaspirina*, also with five congeners in India, exhibits pronounced interspecific variability, and *C. parapontica* is characterized by distinct sublabial rods and hook-shaped supplements. In *Draconema*, four Indian species show marked variation in head morphology and spicules; *D. claparedii*, bearing a distinctive double row of cylindrical rods (double fin) in the posterior part of its body. *Rhynchonema brevituba*, with its ten Indian congeners, is distinguished by its tubular stoma with sclerotized walls and a swollen lip region forming a protruding ring, and shows resemblance to *R. deconincki* Vitiello, 1967.

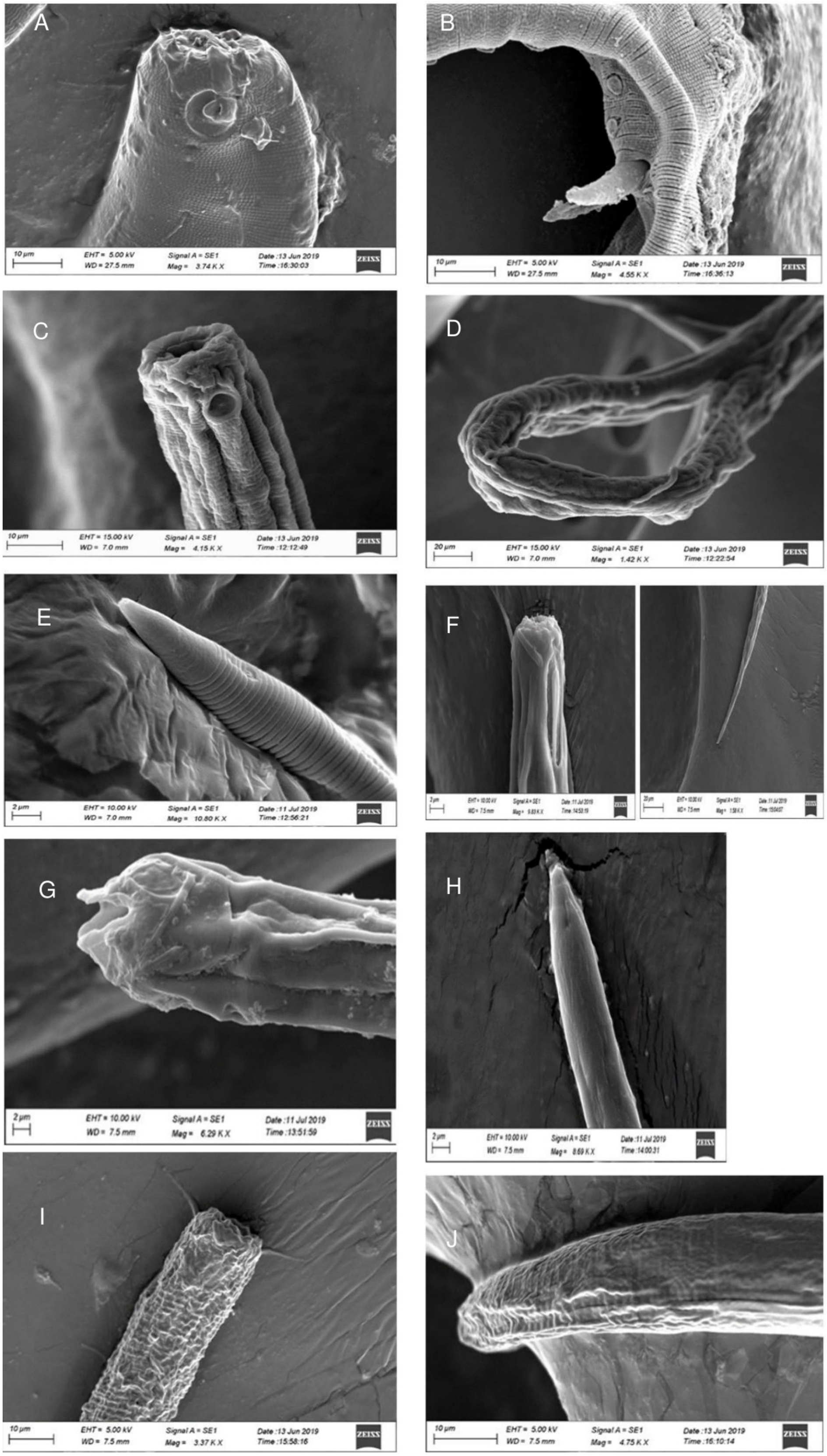

Fig. 3. A and B-*Paracyatholaimus occultus*; C and D-*Xyala striata*; E–*Rhynchonema* sp.; F-*Euchromadora* sp; G and H-*Theristus acer*; I and J-*Ceramonema reticulatum*

Meiobenthic fauna play a critical role in energy flow and nutrient cycling within marine ecosystems (Wołowicz *et al*., 2024). Their pattern of distribution is controlled by abiotic variables such as depth, oxygen content, Sediment grain size, organic matter quality, temperature, salinity, and hydrodynamics, and also biotic interactions. Oxygen-rich environments have higher meiofaunal density, diversity, and biomass owing to enhanced availability of prey such as copepods and nauplii. In contrast, oxygen-deficient environments relate to lower diversity. Chloroplastic pigment equivalents, which reflect primary productivity, are also key in determining meiofaunal biomass and indicate pelagic-benthic coupling. Microhabitat factors such as distance from low tide and microtopography, often overlooked, significantly shape community composition (Macher *et al*., 2024). Environmental filtering, rather than competition, has a stronger influence on community assembly in tropical environments (Macheriotou *et al*., 2023).

Nematodes dominate meiofaunal assemblages—often comprising over 85% of meiofauna and are crucial for decomposition, nutrient cycling, and trophic transfer (Schratzberger and Ingels, 2018). Despite their ecological value, meiofauna are rarely included in environmental monitoring or conservation frameworks. Their small size and rapid responsiveness to environmental shifts make them ideal bioindicators for evaluating ecological health and anthropogenic impacts (Zeppilli *et al*., 2015). The central west coast of India is increasingly subjected to anthropogenic stressors, including tourism, industrial discharge, mining effluents, and habitat modification (Ansari and Ingole, 2002; Patil *et al*., 2011). As a result of their sensitivity, meiofaunal communities are effective bioindicators of benthic environmental condition. This highlights the urgent need to incorporate meiofaunal data into conservation and monitoring. Consistent studies of diversity, when undertaken, uncover patterns of degradation or recovery, guiding conservation priorities. Institutions such as the Zoological Survey of India (ZSI) have made significant progress in documenting faunal biodiversity at the macroscopic level, but microscopic fauna remain largely underrepresented. Integrating molecular methods may enhance species resolution and functional understanding, while long- and seasonal-term approaches may assess meiofaunal stress resilience and recovery under pollution and climatic conditions.

Conclusion

Meiofaunal assemblages are some of the most sensitive indicators of both natural and anthropogenic disturbances in marine ecosystems. Their ecological significance, particularly in maintaining ecosystem integrity and resilience, is significant but often overlooked. A comprehensive understanding of their diversity, spatial distribution, and functional roles is essential for accurate assessments of environmental health. Such knowledge not only refines biomonitoring frameworks but also strengthens the scientific basis for ecosystem-based management and marine spatial planning. It is essential to acknowledge that all faunal groups, including micro, meio, and macrofauna, are closely interconnected and collectively sustain the ecosystems they inhabit. Therefore, it is imperative to adopt integrative, multi-trophic research and conservation strategies. This holistic approach is crucial for achieving the long-term goals of marine biodiversity restoration, protection and sustainable use.

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Author contributions

Conceptualization: GS, SB; Methodology: GS, CS; Data Collection: GS, SB, CS; Data Analysis: GS; Writing Original Draft: FSR, GS; Writing Review and Editing: FSR; Supervision: GS

Data availability

The data is not available elsewhere and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of samples/ protected environments.

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First record of the mole crab, *Emerita emeritus* (Linnaeus, 1767), from the Gujarat coast, India

Piyush Vadher[1], Hitesh Kardani[1]*, Imtiyaz Beleem[2,3], Rajkumar Dabhi[1], Ajay Ram[1], Pinak Bamaniya[1] and Sunil Shekh[1]

[1]Fisheries Research Station, Kamdhenu University, Sikka -361140, Gujarat, India.
[2]Estonian Marine Institute, University of Tartu, Mäealuse 14, Tallinn-12618, Estonia.
[3]Office of Chief Conservator of Forest, Marine National Park, Jamnagar - 361001, Gujarat, India.

*Correspondence e-mail: hiteshkardani@gmail.com
ORCiD: https://orcid.org/0000-0002-8112-5061

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Short Communication

Abstract

Emerita emeritus (Linnaeus, 1767) collected from Navi Bandar in Gujarat represents the first record of this species, genus, and family from the coastal waters of Gujarat. Five males and nine females were found buried in the sandy substrate of the beach. Two species of *Emerita* within the family of Hippidae have been reported from various coastal regions of India. This report provides a detailed morphological description of *E. emeritus*, along with notes on its habitat and distribution.

Keywords: *Hippidae, mole crab, new record, taxonomy, Gujarat*

Introduction

The family Hippidae Latreille, 1825, commonly known as mole crabs, consists of a small group of sand-burrowing crustaceans typically found in subtidal zones across the globe. Much like nature's beach miners, these crabs tunnel through sand in search of food and protection. The family currently includes three genera and 30 species globally. These organisms are predominantly distributed along sandy beaches in temperate, tropical, and subtropical regions (Osawa *et al*., 2010; Mantelatto *et al*., 2023; WoRMS, 2025). Six species belonging to three genera within the family Hippidae have been reported from various coastal regions of India (Patel *et al*., 2022). The genus *Emerita* Scopoli, 1777 is distinguished from the other two genera within the family by the antennal flagellum, which is at least as long as the carapace and densely covered ventrally with long plumose setae. Additionally, the dactylus of the first pereiopod is lamellate and broad (Osawa *et al*., 2010). The genus comprises approximately 13 species distributed globally, typically inhabiting intertidal and upper subtidal sandy marine environments. Of these, two species of *Emerita,* namely, *Emerita emeritus* (Linnaeus, 1767) and *Emerita holthuisi* (Sankolli, 1965), have been reported from Indian waters (Pillai and Thirumilu, 2005; Sharma *et al*., 2016; Patel *et al*., 2022; Mantelatto *et al*., 2023; WoRMS, 2025). *Emerita emeritus* typically inhabits sandy beaches, with a preference for areas dominated by coarse sand fractions (Mahapatro *et al*., 2018; Rahmatuloh *et al*., 2020). This species is distributed across various regions of the Indo-Pacific Ocean, including India, Indonesia, Malaysia, Sri Lanka, Thailand, and Vietnam (Efford, 1976). A review of the literature on Anomuran crabs of India reveals that the family Hippidae has not previously been reported from the waters of Gujarat (Patel *et al*., 2022). Therefore, this study reports a new record of the family Hippidae, genus *Emerita*, and species *Emerita emeritus* from Gujarat coastal waters.

Material and methods

The Navi Bandar is a small coastal village situated at the mouth of the Bhadar River, approximately 35 km east of Porbandar, India. The river features a wide estuarine region that historically served as a safe harbour; however, the regular formation of sand bars at its mouth now restricts navigation to small fishing boats only. The coastline of Navi Bandar is characterised by sandy and rocky substrates. A total of fourteen specimens of *E. emeritus*, comprising nine females (including two ovigerous individuals) and five males, were collected from the sandy intertidal zone at Navi Bandar (21° 26′ 59.8″ N; 69° 47′ 03.0″ E), Gujarat, India (Fig. 1). Specimens were found buried in the sandy upper intertidal zone along the

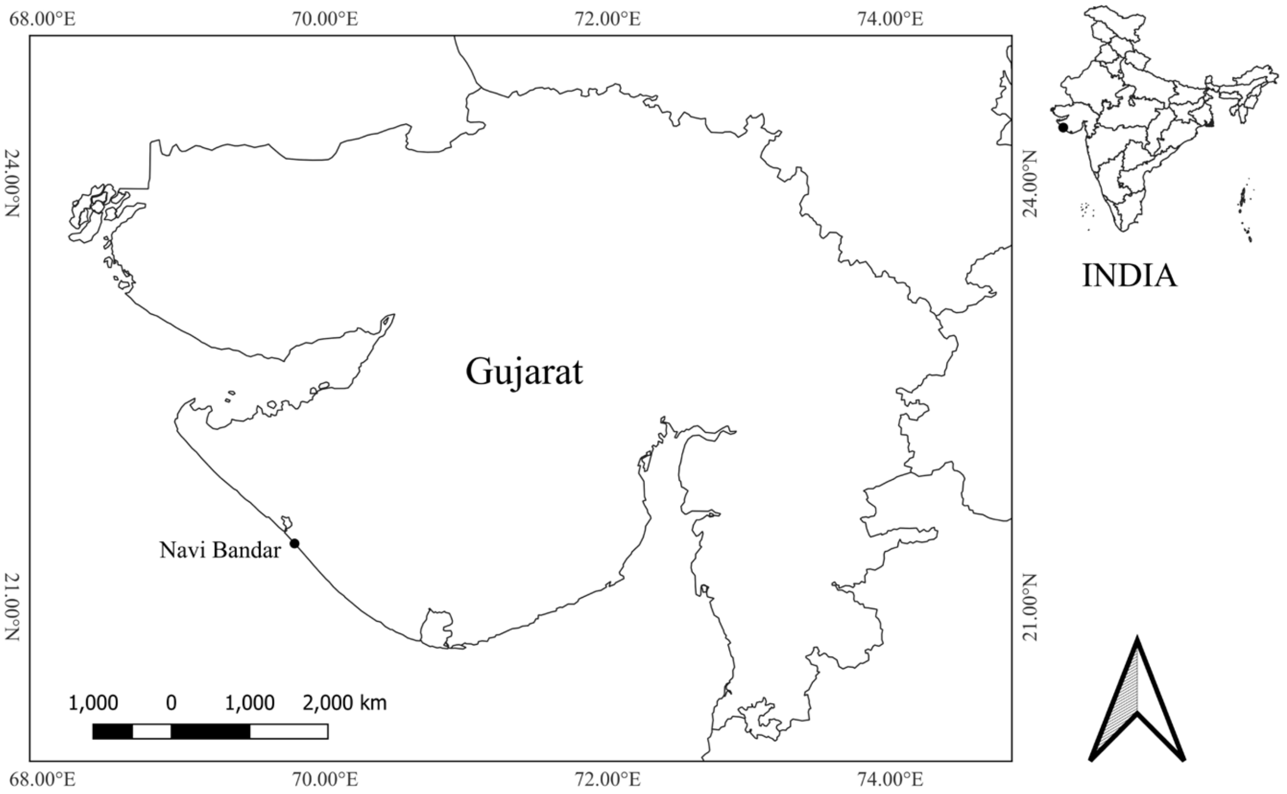

Fig. 1. Map of the study area

Navi Bandar, Gujarat. The collected specimens were transferred to the laboratory of the Fisheries Research Station, Kamdhenu University, Sikka. The specimens were cleaned, photographed, and subjected to a detailed examination of their morphological characters. Taxonomic identification was performed using standard references (Sankolli, 1965; Mahapatro *et al.*, 2018; Farajallah *et al.*, 2025). Specimens were preserved in 70 % ethanol and deposited under accession number FRSACDA-07 in the Museum of the Fisheries Research Station, Kamdhenu University, Sikka. The size of the specimens is given as carapace length (CL), measured from the tip of the rostrum (frontal lobe) to the posterior edge of the carapace (excluding the abdomen/telson), and total length (TL), measured from the tip of the rostrum (frontal lobe) to the distal end of the telson (Fig. 2B). The body weight of each crab was recorded using a weighing balance and expressed in grams.

Results and discussion

Systematics

Order : Decapoda Latreille, 1802
Infraorder : Anomura MacLeay, 1838
Superfamily : Hippoidea Latreille, 1825
Family : Hippidae Latreille, 1825
Genus : *Emerita* Scopoli, 1777
Emerita emeritus (Linnaeus, 1767) (Fig. 2)

Materials examined

14 specimens, FRSACDA-07, five males (1) cl = 12 mm, tl = 14 mm, weight = 0.53 gm, (2) cl = 12 mm, tl = 14 mm, weight = 0.66 gm, (3) cl = 12 mm, tl = 14 mm, weight = 0.50 gm, (4) cl = 13 mm, tl = 15 mm, weight = 0.78 gm, (5) cl = 13 mm, tl = 15 mm, weight = 0.89 gm, seven females (1) cl = 13 mm, tl = 15 mm, weight = 0.72 gm, (2) cl = 13 mm, tl = 15 mm, weight = 0.90 gm, (3) cl = 13 mm, tl = 15 mm, weight = 0.96 gm, (4) cl = 14 mm, tl = 16 mm, weight = 103 gm, (5) cl = 14 mm, tl = 16 mm, weight = 0.99 gm, (6) cl = 14 mm, tl = 16 mm, weight = 0.98 gm, (7) cl = 14 mm, tl = 16 mm, weight = 105 gm, two ovigerous females (1) cl = 14 mm, tl = 16 mm, weight = 112 gm, (2) cl = 14 mm, tl = 16 mm, weight = 102 gm, (21°26′59.8″N 69°47′03.0″E) of Navi Bandar, Gujarat, coll. by Hitesh Kardani and Piyush Vadher, 03 May, 2025.

Diagnosis

Body almost cylindrical. Carapace frontal margin tridentate; 3 lobes slender, elongate with distinct horny tips (Fig. 2A). Median lobe triangular, acute, distinctly separated from lateral lobes, gap exceeds basal width of median lobe. Anterolateral margin smooth. Dorsal transverse rugae are crowded, rarely interrupted. Postfrontal and postgastric furrows are well defined. Hepatic region strongly grooved. Posterolateral margin rounded. Ocular peduncles are slender, elongated, and extend well beyond the

Fig. 2. *Emerita emeritus* (Linnaeus, 1767) (A) Dorsal view; (B) Ventral view; (C) First pereiopod; (D) Antennules flagellum. Scale bars: 10 mm

spines of antennal segment II. Antennules densely hairy (Fig. 2D); flagellum with 25-85 articles. Antenna of segment II bears 3 distal spines with horny tips; the median spine is longest. Two distinct oblique ridges with fine movable spinules are present, aligned with the ventral tooth. First ridge arises mid-segment, follows ventral spine; second ridge lies just below. The dorsal side between the median and dorsal teeth has several short oblique rugae. Merus of the third maxilliped rectangular; 1.5 times longer than wide. Outer anterolateral angle produced, tooth-like, often with a horny tip (may be broken); antero-internal lobe low, triangular, but prominent. Dactylus of first pereiopod broadly ovate (Fig. 2C), length 1.8-2.0 greatest width; terminates in single spine. Distal third of lower margin bears 4-5 horny, movable spines. Upper margin near tip with 1-3 spines (usually 2), often short with shallow bases, inner margin typically with 4 spines in distal one-third of lower margin. Entire animal pink in color; appendages pale yellowish; eyes reddish; overall semi-translucent with visible internal segmentation, egg mass bright yellow.

Distribution

Asian sea (Milne Edwards, 1837); Indian Ocean (Linnaeus, 1767); Indonesia (Efford, 1976; Rahmatuloh *et al.*, 2020; Farajallah *et al.*, 2025); Malaysia (Efford, 1976); Sri Lanka (Efford, 1976); Thailand (Efford, 1976); Vietnam (Efford, 1976).

India: Gujarat (Present study); Goa (Efford, 1976); Karnataka (Patil, 1951); Kerala (Efford, 1976); Lakshadweep Islands (Nagabhushanam and Rao, 1972); Tamil Nadu (Sankolli, 1965; Efford, 1976); Andhra Pradesh (Efford, 1976); Odisha (Efford, 1976; Mahapatro *et al.*, 2018).

Remarks

The detailed morphological characteristics of the present specimen are in strong agreement with the descriptions (Sankolli, 1965; Mahapatro *et al.*, 2018; Farajallah *et al.*, 2025). *Emerita emeritus* similar to *E. holthuisi* Sankolli, 1965, but differs in having a broadly ovate dactylus of the first pereiopod with spines on both margins, while *E. holthuisi* has a more slender dactylus bearing spines only on the lower margin. The frontal lobes of *E. emeritus* are long and slender, whereas in *E. holthuisi*, they are shorter and broader. Additionally, *E. emeritus* exhibits more densely crowded dorsal rugae, while those in *E. holthuisi* are more spaced and interrupted. The outer anterolateral angle of the third maxilliped is tooth-like and produced in *E. emeritus,* but is rectangular and not produced in *E. holthuisi* (Sankolli, 1965).

Emerita emeritus resembles *E. pangandaran* Farajallah, Hanim, Putri and Wardiatno, 2025 but differs from *E. pangandaran* in several key characters. While both species share general features such as a flattened, ovate dactylus with a terminal spine and acutely pointed frontal lobes, *E. emeritus* typically has a smooth anterolateral carapace margin and distinct spines on the outer margin of the dactylus, which are absent in *E. pangandaran*. The outer angle of the third maxilliped merus is tooth-like and produced in *E. emeritus*, but rectangular and unproduced in the *E. pangandaran*. Additionally, *E. emeritus* exhibits a different configuration in the armature of the anterior carapace margin, which contrasts with the more reduced or altered pattern observed in *E. pangandaran* (Farajallah *et al.*, 2025).

Conclusion

The present study reports the first occurrence of *Emerita emeritus* (Linnaeus, 1767) from Gujarat, extends the known distribution range of *E. emeritus* to the northwestern coast of India, and highlights the underexplored diversity of intertidal crustaceans in Gujarat waters. Detailed morphological analysis confirms the identity of the species and distinguishes it from closely related taxa, such as *E. holthuisi* and *E. pangandaran*. This baseline record underscores the need for continued taxonomic and ecological surveys along India's western coastline to better understand and conserve its marine biodiversity.

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Author contributions

Conceptualisation: PV, HK, IB; Methodology: PV, HK, IB; Data Collection: PV, HK; Data Analysis: PV, HK, IB, RD, AR, PB, SS; Writing Original Draft: PV, HK, RD, AR, PB, SS; Writing Review and Editing: HK, IB; Supervision: HK.

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of samples/ protected environments.

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Publisher's note

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On the occurrence of the elusive cardinalfish, *Apogon fugax* (Teleostei, Apogonidae), in the Bay of Bengal

A. Murugan[1], G. Mahadevan[2]* and S. Ragul[3]
[1]Crab Meat Processors Association, P&T colony, Tuticorin-628 008, Tamil Nadu, India.
[2]Kerala State Biodiversity Board, Thiruvananthapuram- 695 003, Kerala, India.
[3]College of Fisheries Science, Kamdhenu University, Veraval- 362 265, Gujarat, India.

*Correspondence e-mail: marinemahadevan@gmail.com
ORCiD: https://orcid.org/0000-0002-2654-4087

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Short Communication

Abstract

The cardinalfish *Apogon fugax* Gon, Bogorodsky, Mal and Alpermann, 2020, was originally described from the Red Sea, Myanmar, and Australia. Three specimens (64.0–72.5 mm SL) were collected from the bycatch of demersal trawlers operating at depths of 30–70 m off Pazhayar, Tamil Nadu. This record represents a range extension from the previously known locations in the Indian coast (Gujarat, Kerala) to the Coromandel coast, the east coast of India. The species was identified based on a detailed morphometric analysis and meristic counts, which align with the original description, including key diagnostic characters such as 10–11 lower gill rakers and a distinctive colour pattern featuring a series of black dots on the first dorsal fin. Given the high diversity of cardinalfishes (Apogonidae) in Indian waters and their prevalence in trawl bycatch, this study underscores the importance of continued biodiversity assessments.

Keywords: *Bottom trawl, bycatch, Coromandel coast, range extension, rocky crevices*

Introduction

Globally, the family Apogonidae exhibits significant diversity, with a contemporary framework recognising four subfamilies: Apogoninae (34 genera, 354 species), Pseudamiinae (3 genera, 23 species), Amioidinae (2 genera, 3 species), and Paxtoninae (1 genus, 1 species), collectively amounting to 40 valid genera and 381 species (Fricke *et al*., 2026). Within the Indian EEZ, the known apogonid fauna, estimated at 77 species spanning 26 genera, is predominantly composed of members from the Apogoninae and Pseudamiinae subfamilies (Saravanan *et al*., 2017; Vishnupriya *et al*., 2020; Kosygin *et al*., 2024). A key feature of this regional diversity is the limited documentation of the genus *Apogon*; despite its global richness of 55 species, only three have been formally recorded from Indian waters in the past (Rajan *et al*., 2021; Ragul *et al*., 2024; Kosygin *et al*., 2024).

The recent description of *Apogon fugax* from the Red Sea, Pakistan, Myanmar, and Western Australia (Gon *et al*., 2020; Moazzam and Osmany, 2023) was followed by its report from the Gujarat (Ragul *et al*., 2024) and Kerala (Suyani *et al*., 2025) coast, representing a significant range extension into Western India (Ragul *et al*., 2024). The present record of *A. fugax* from rocky crevices at 45–60 m depth on the Coromandel coast further extends its known distribution to the eastern coast of India. As a predominantly reef-associated taxon, its occurrence in these non-reef areas suggests the presence of structurally complex habitats, such as rocky substrata, that provide analogous ecological niches.

Apogonids are a ubiquitous component of warm temperate to tropical demersal assemblages, often ranking among the most diverse and abundant groups in reef ecosystems (Bellwood and Wainwright, 2002). Their ecological role as nocturnal mesopredators, combined with their susceptibility to bottom-trawl bycatch and value in the aquarium trade, underscores their conservation significance. The present work reports the first record of *A. fugax* from the eastern coast of India, representing a range extension from its known distribution along the western coast. The species identification is corroborated through a comprehensive analysis of its morphology, meristic counts, and live colouration.

Material and methods

Field surveys were undertaken from the trawl landing centres on the Coromandel coast of Tamil Nadu, India, in August 2023. During this period, a total of three specimens of *A. fugax*, ranging from 64.0–72.5 mm standard length (SL), were collected from the bycatch of Pazhayar (11° 21′32″ N 79°49′ 22″ E) bottom trawlers (cod end mesh sizes ranging from 18 to 35 mm). The fishing was mostly focused on demersal species *Metapenaeus* spp. at a depth range of 30 to 70 m and was undertaken mostly during the night hours, with the catch being landed in the morning hours. The specimens were procured from the bycatch of commercial trawlers at the Pazhayar landing centre.

The collected specimens were transported to the laboratory, and photographs were taken for documentation. Morphometric measurements were conducted using a Mitutoyo CD-6″ASX® digital Vernier calliper, ensuring precision to the nearest 0.1 mm. Measurements and proportions follow Hubbs and Lagler (1954) and Gon and Randall (2003), with morphometric characters expressed as percentages of standard length (SL) and head length (HL). The specimens were identified to the species following Gon *et al.* (2020). To ensure effective preservation, the collected materials were immersed in a 10% formalin solution and subsequently deposited in the Marine Biology Regional Centre, Zoological Survey of India, Chennai, Tamil Nadu, India, for future reference.

Results

Systematic position

Family: Apogonidae Günther, 1859
Subfamily: Apogoninae Günther, 1859
Genus: *Apogon* Lacepède, 1801
Apogon fugax Gon, Bogorodsky, Mal and Alpermann, 2020
Elusive cardinalfish (Fig. 1)

Apogon fugax Gon, Bogorodsky, Mal and Alpermann, 2020: 485, Fig. 1 and Table 3 (type locality: Jizan coast, Saudi Arabia, southern Red Sea). —Moazzam and Osmany, 2023: 50, Fig.

Table 1. Comparison of morphometric characters of *Apogon fugax* from the Tamil Nadu coast (present study) with previous records

Morphometric characters	Present study (Tamil Nadu)	Gon *et al.* (2020)	Ragul *et al.* (2024)	Suyani *et al.* (2025)
Standard Length (mm)	64.0–72.5	42.5–59.6	46.7–58.0	75.6–84.3
In % Standard Length				
Head Length	39.8–41.1	41.9–45.4	38.7–42.8	40.2 41.8
Snout Length	6.4–7.6	7.5–8.9	6.6–7.7	5.0–6.6
Eye Diameter	10.3–11.9	11.4–13.4	10.7–12.0	10.7–12.3
Body Depth	31.6–32.5	30.7–34.1	28.6–33.1	31.8–34.7
Pre-dorsal Length	40.7–41.1	41.4–43.1	41.3–42.8	37.5–39.7
Pre-ventral Length	34.7–37.4	37.2–40.1	35.3–38.9	32.3–38.2
Pre-anal Length	59.5–62.9	61.8–64.0	60.5–62.0	54.2–62.6
1st Dorsal Fin Base Length	12.0–12.5	–	12.2–13.0	13.4–14.0
2nd Dorsal Fin Base Length	13.3–13.7	–	13.7–13.9	14.5–15.0
1st Dorsal Fin Spine Length	8.4–8.8	8.6–10.5	8.6–8.7	7.8–8.7
2nd Dorsal Fin Spine Length	16.0–16.9	16.5–17.9	16.7–17.2	14.8–15.9
3rd Dorsal Fin Spine Length	15.4–16.6	15.8–17.1	14.7–16.8	15.8–16.1
Spine of 2nd Dorsal Fin Length	14.2–14.4	13.8–14.6	12.8–14.6	12.0–13.1
Anal Fin Base Length	13.1–13.6	–	13.7–13.9	13.3–13.8
1st Anal Fin Spine Length	3.1–3.4	2.9–3.1	3.2–3.4	2.5–4.3
2nd Anal Fin Spine Length	12.3–12.7	12.6–12.7	12.8–12.9	10.8–11.6
Pectoral Fin Length	28.7–28.8	29.2–30.3	29.3–29.9	27.5–29.0
Ventral Fin Length	22.0–23.6	23.1–24.0	23.1–24.1	19.4–23.3
Ventral Fin Spine Length	14.0–14.4	14.2–15.1	14.5–14.6	12.1–12.8
Caudal Fin Length	32.4–34.9	31.4–35.5	29.4–32.1	30.5–32.4
Caudal Peduncle Length	25.7–27.1	25.9–28.2	24.6–27.5	26.4–30.3
Caudal Peduncle Depth	13.6–14.4	13.4–14.0	13.7–14.9	13.7–14.7

Fig. 1. Photograph of fresh *Apogon fugax* (ZSI/MBRC/F.3358) from Pazhayar Fishing Harbour, southeastern coast of India, Tamil Nadu. Scale = 10 mm

4., Ragul *et al.*, 2024: 1, Fig. 1 and Table 1.—Suyani *et al.*, 2025: 1, Fig. 1 and Table 1.

Material examined

ZSI/MBRC/Reg No. F.3358, 3 ex., 64.0–72.5 mm SL (Fig. 1), Pazhayar Fishing Harbour, southeastern coast of India, Tamil Nadu, 11°21′32″N 79°49′22″E, collected by A. Murugan, 15 Aug. 2023.

Diagnosis

Apogon fugax is distinguished from congeners by the following combination of characters: dorsal-fin rays VI + I,9; anal-fin rays II,8; pectoral-fin rays 12; total gill rakers on first arch 14–15 (4+10–11). Live colouration bright reddish to dark orange; first dorsal fin with a distinct mid-line series of black dots.

Description

Dorsal-fin rays VI + I,9; anal-fin rays II,8; pectoral-fin rays 12; pelvic-fin rays I,5; gill rakers on first arch 4 + 10–11, total 14–15.

Body deep compressed; depth 31.6–32.5% SL. Head length 39.8–41.0% SL. Scales ctenoid; single large scale between the first dorsal fin and lateral line. Snout to first dorsal fin origin 40.7–41.1% SL; to anal fin origin 59.5–62.9% SL; to pelvic fin origin 34.7–37.4% SL. Head profile straight; nape elevated. Head width at preopercle 13.3–13.8% SL. Opercular margin weak, without serrations. Preopercle margin serrated. Snout elevated, length 6.4–7.6% SL. Eye large, diameter 10.3–11.9% SL. Mouth terminal; maxilla reaching to below the anterior half of the pupil; upper jaw 20.3–21.6% SL; lower jaw 22.0–24.8% SL. Jaws with villiform teeth. Tongue with a short lobe. First dorsal fin triangular, base 12.0–12.5% SL; first spine shortest (8.4–8.8% SL), second longest (16.0–16.9% SL), third intermediate (15.4–16.6% SL). Second dorsal fin base 13.3–13.7% SL; spine 14.1–14.4% SL. Pectoral fin elongate, 28.7–28.8% SL. Pelvic fins short, 22.0–23.6% SL; spine 14.0–14.4% SL. Anal fin base 13.1–13.5% SL. Caudal fin narrow, elongate, forked, length 32.4–34.9% SL. Caudal peduncle slender, compressed; length 25.7–27.1% SL, width 6.1–6.7% SL, depth 13.6–14.4% SL. For detailed morphometrics, see Table 1.

Colouration

Fresh: Body bright reddish to dark orange (Fig. 1). First dorsal fin with a mid-line series of black dots between second and third membranes. Other fins are orange; the caudal fin distal part, second dorsal fin base, pelvic fin base, and anal fin base are translucent.

Colour in formalin: Body pale. First dorsal fin black dots prominent. Paired and unpaired fins are pale yellowish.

Distribution and habitat

Apogon fugax is known from the Indo-Pacific waters: the Red Sea, Pakistan, India, Myanmar, and Western Australia (Gon *et al.*, 2020; Moazzam and Osmany, 2023). From Indian waters, it is only known from the western coast, *i.e.*, Veraval, Gujarat (Ragul *et al.*, 2024) and Cochin, Kerala (Suyani *et al.*, 2025). This present study reports its occurrence along the southeastern coast, off Pazhayar, Tamil Nadu.

Discussion

Among the four apogonid subfamilies, Apogoninae is the most diverse, encompassing the majority of species and exhibiting the greatest morphological and ecological variation, including the occurrence of bioluminescence (Mabuchi *et al*., 2014). In Indian waters, cardinalfishes are widely distributed across diverse ecosystems. Regional studies report varying levels of diversity: 41 species from the Gulf of Mannar (Joshi *et al*., 2016), 48 species from the Andaman and Nicobar waters (Rajan *et al*., 2021), and fewer species from the Lakshadweep Islands and the west coast (Jones and Kumaran, 1980; Kumar *et al*., 2019). Comprehensive national checklists estimate the Indian apogonid fauna at 77 species across 26 genera (Gopi and Mishra, 2015; Saravanan *et al*., 2017; Kosygin *et al*., 2024), indicating that taxonomic clarity and exact species diversity require further research.

The genus *Apogon* sensu stricto is now represented by three species in Indian waters: *A. coccineus*, *A. ceramensis*, and the recently reported *A. fugax* (Rajan *et al*., 2021; Ragul *et al*., 2024; present study). *A. fugax* is distinguished from other Indian *Apogon* species by its lack of a semi-transparent body and from other members of the *A. talboti* group by a lower gill raker count (10–11).

This study confirms the first record of *Apogon fugax* from the southeastern coast of India, extending its known range. The finding underscores significant gaps in our understanding of apogonid taxonomy and distribution in Indian waters, highlighting the need for further research to support the conservation of cardinal fishes.

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Author contributions

Conceptualisation: AM; Methodology: AM; Data Collection: AM; Data Analysis: GM, SR; Writing Original Draft: AM; Writing Review and Editing: GM, SR; Supervision: AM. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability

All relevant datasets supporting the conclusions of this article are included within the article.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of samples/ protected environments.

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Publisher's note

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Abstract

The abstract should be clear, descriptive and not longer than 300 words; should give readers a clear overview of the study, allowing them to quickly understand its purpose, approach, key findings, importance and potential future applications. It should provide a very brief introduction to the problem and a statement about the methods used in the study. This should generally be followed by a brief summary of results, including numerical data (means and standard errors, for example). The abstract should end with an indication of the significance of the results. An abstract is often presented separately from the article while indexing/ abstracting, so it must be able to stand alone by itself.

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Immediately after the abstract, provide a maximum of six keywords, avoiding general and plural terms and multiple concepts (avoid, for example, "and", "of"). Be sparing with abbreviations: only abbreviations firmly established in the field are to be given. The keywords will be used for indexing purposes.

Introduction

The introduction should provide a background context of the work and highlight the current state of knowledge in the field, identifying knowledge gaps or unresolved issues that the study addresses. It should clearly state the research objectives or questions and explain the significance of the study, outlining its potential impact. A brief mention of the methodology can be included to give an overview of the approach. Finally, the introduction should define the scope and limitations of the research, setting the stage for the rest of the paper, besides capturing the reader's attention.

Material and methods

The Materials and Methods section should provide a detailed description of how the study was conducted (including necessary citations) to ensure reproducibility by other workers. It should include dates, the study design, listing of all materials, organisms, or data sources used, along with any equipment, chemicals, or reagents. It should outline the experimental or analytical procedures followed, including sample preparation, data collection, and statistical analyses. If relevant, the study area is to be described, and variables such as independent, dependent, and control factors are identified. Any ethical approvals, particularly in studies involving humans or animals, are to be indicated here to ensure compliance with research standards.

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The Results section should contain the key findings of the study clearly and objectively without interpretation. Data are summarized using tables, figures, graphs and or photographs to enhance clarity as needed. The section should highlight the most important findings that address the research questions, reporting the outcomes of statistical analyses, including significance levels and confidence intervals. Observed trends, patterns, or relationships are described, and any unexpected or negative results are also noted if relevant. This section focuses solely on presenting the findings, leaving their interpretation for the Discussion section.

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The Discussion section should focus on the findings of the study in relation to the research objectives, explaining their significance and meaning. It should compare the results with previous studies, highlighting similarities, differences, or new insights that contribute to the existing body of knowledge providing relevant and recent citations. The broader implications of the findings are to be discussed, addressing their impact on the field, theory, or practice. Any limitations of the study that could have influenced the results are to be incorporated, and suggestions for future research are provided to address unresolved questions or new directions based on the findings.

(Authors may combine Results and Discussion if so desired)

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The Acknowledgements section should recognise individuals, institutions, projects and funding sources that supported the research but are not listed as authors. It includes gratitude for financial support, such as grants or fellowships, acknowledges the contributions of colleagues, advisors, or collaborators who provided significant assistance, and mentions any institutions or organizations that offered resources, facilities, or other forms of support. Additionally, it may include thanks to ethical or administrative bodies that approved the research.

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Dr V. V. R. Suresh
Principal Scientist, ICAR-CMFRI, Kochi- 682 018
E-mail: sureshvr64@yahoo.com; vettath.suresh@icar.org.in

Editors
Dr S. Lakshmi Pillai
Principal Scientist, ICAR-CMFRI, Kochi-682 018
Email: slakshmipillai@rediffmail.com; lakshmi.pillai@icar.org.in

Dr Reshma Gills
Senior Scientist, ICAR-NAARM, Hyderabad-500 030
Email: reshma1818@gmail.com; reshma.gill@icar.org.in

Dr P. P. Suresh Babu
Principal Scientist, ICAR-CMFRI, Kochi-682 018
Email: sbabu78@yahoo.com; suresh.babu1@icar.org.in

Dr P. R. Divya
Principal Scientist, Centre for PAGR, Kochi- 682 018
Email: divyanbfgr@gmail.com

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