

# Collaborative multi-stakeholder approach for preliminary exploratory trials of mesopelagic resources in the Indian EEZ

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## Abstract

This study reports findings from preliminary commercial trials conducted in India's Exclusive Economic Zone (EEZ) to explore the commercial potential of mesopelagic resources in the south-eastern Arabian Sea along the Karnataka coast. Two modified commercial multiday trawl vessels equipped with navigation and fish detection systems conducted 15 midwater trawl hauls at depths of 300-800 m, during night time over a three month period (January, April, and May 2025). The trials employed a midwater trawl with a 70 m headline, 45 mm mesh, and 20 mm codend mesh, specifically designed for mesopelagic operations, targeting species exhibiting diel vertical migration. A participatory framework involving fishers, boat owners, and industry stakeholders, was adopted to improve operational efficiency, facilitate technology adoption, and support value chain development. The fishing trials yielded a species rich catch comprising 40 species belonging to 38 families and 20 orders, with Ophidiidae (23.32%), Pentanchidae (15.94%), and Trachichthyidae (15.05) being dominant families. The average catch per haul was  $\pm 1.8$  t, with a catch rate of approximately 120 kg h<sup>-1</sup>. Operational and management challenges included gear failures, post-harvest spoilage due to the fragile nature of several species and inadequate cold storage facilities. Jellyfish bycatch was observed as an important operational and ecological challenge. Modifications to fishing gear such as the use of Ethylene Vinyl Acetate (EVC) floats, improved gear resilience during deep water operations. Overall, the study highlights the opportunity for further exploration of mesopelagic resources in India's deep waters, while emphasising the need for further gear innovation, systematic abundance mapping, targeted ecological research, and continued stakeholder collaboration, for sustainable development.

## Introduction

Indian marine fish production hovered around 2.7 million t per annum over the decade up to 2010 (Joseph and Jayaprakash, 2003), before increasing to approximately 3.9 million t in 2012 (CMFRI, 2013). Production fluctuated within this higher range until 2020 (CMFRI, 2023). The fisheries sector supports nearly 4 million livelihoods. During 2022-23, it generated significant foreign exchange earnings of approximately 1.73 million t

of seafood worth ₹63,969.14 crore (USD 8.09 billion) (MPEDA, 2023). However, the rising exploitation of traditional coastal and pelagic fisheries (FAO, 2022) has heightened the quest for alternative marine resources. To meet the growing demand for marine fish primarily for food, pharmaceuticals, and animal feed, there is an urgent need to explore underutilised deep-sea (200-2000 m) and mesopelagic (200-1000 m) resources.

The mesopelagic zone, spanning depths from 200 to 1000 m, harbors an immense

and largely untapped biomass of organisms such as myctophids (lanternfishes), krill, and squids (Nelson, 2006; Eschmeyer *et al.*, 2022). These species play a crucial role in oceanic food webs and biogeochemical cycles, particularly in the vertical transfer of carbon through diel vertical migration. This process underscores the ecological importance of mesopelagic species in global carbon cycling and energy transmission within the pelagic ecosystem (Irigoien *et al.*, 2014). Globally, mesopelagic resources are being considered for their potential to support sustainable fisheries and to serve as sources of protein, nutraceuticals, and fishmeal in the face of declining coastal fish stocks. For instance Lam (2005) estimated 263 million t of mesopelagic resources in the Western Indian Ocean (FAO, 2022), highlighting its potential for commercial exploitation in this region. Furthermore, Irigoien *et al.* (2014) estimated the myctophid potential in the Indian Ocean at 365 million t, which accounts for 3% of the world's total myctophid biomass. Additionally, Valinassab *et al.* (2007) reported daily myctophid catches ranging from 20–28 t during commercial fishing trials in the Sea of Oman.

In recent years, there has been a growing emphasis on participatory approaches in fisheries research, recognising the value of local ecological knowledge, industry experience, and shared stewardship (Wedemeyer *et al.*, 2019). In this context, the present study adopted a participatory framework, engaging active fishers, boat owners, and industry partners in the design and execution of exploratory mesopelagic fishing trials. Such collaboration is critical for ensuring technology adoption, improving the practicality of operational methods, and building trust among stakeholders, particularly in uncharted fishery frontiers like the mesopelagic zone. Historical acoustic investigations of the Deep Scattering Layer (DSL) in the Indian EEZ documented substantial biological concentrations at depths of approximately 200–540 m (Menon and Prabha Devi, 1990). More recently, ICAR-Central Marine Fisheries Research Institute (ICAR-CMFRI) has highlighted the potential of mesopelagic resources in the Indian EEZ, with a preliminary estimate of approximately 1.6 million t of harvestable resources, while emphasising the need for further assessment and detailed mapping (Thomas *et al.*, 2024). Harnessing these resources could contribute to nutritional security, support the fish processing industry, and open new economic opportunities. However, scientific understanding and technological readiness for commercial scale exploitation remain limited. Pauly *et al.* (2021) underlined significant gaps related to biomass estimation, harvesting techniques and sustainable use of these resources, emphasising that mesopelagic fisheries are still in an exploratory phase.

Prior research has highlighted the significant potential for mesopelagic resources in the Indian Ocean region. Meera *et al.* (2024) documented the rich diversity and distribution of myctophids in the western Indian Ocean, indicating their widespread occurrence in the region. Menon (2002) reported higher biomass estimates during night sampling at several latitudes in the Indian Ocean, indicating the effect of diel vertical migration on the availability of resources for fishing operations. Boopendranath *et al.* (2012a) estimated a catch of 3676 t of myctophids from deep-sea trawlers operating off the south-west coast of India during 2009 and 2010, providing evidence for the commercial viability of these resources.

Despite the apparent potential, mesopelagic fisheries face numerous challenges, including technological barriers to harvesting, rapid post-capture spoilage, limited information on species composition

and ecology, and concerns about environmental sustainability. Furthermore, effective gear designs, handling techniques, and value chain development are still in their early stages. However, no commercial-scale exploratory fishing trials targeting mesopelagic resources have been systematically documented from the Indian EEZ, particularly along the Karnataka coast. The present study was carried out to assess the feasibility and sustainability of the commercial exploitation potential of mesopelagic resources along the Karnataka coast within the Indian EEZ. The specific objectives were to assess the feasibility of exploring mesopelagic resources using experimental fishing gear, document the species composition, biomass, and size distribution of the catch, and identify key environmental parameters associated with distribution and abundance of mesopelagic resources.

## Materials and methods

### Study area and period

Three preliminary mesopelagic fishing trials were conducted in the south-eastern Arabian Sea off the south-west coast of India, specifically along the Karnataka coast, in January, April, and May 2025. Each trial spanned five days and was conducted within the geographic coordinates extending between 12°35'N and 14°01'N and 73°13'E and 73°36'E. The operations targeted a depth gradient ranging from 200 to 1000 m to explore the availability of mesopelagic resources in the offshore waters of Karnataka. The trials also sought to evaluate species composition, abundance, and gear performance across varying depths and seasonal conditions.

### Vessels and gear specifications

The exploratory fishing trials were conducted using two commercial multiday trawl fishing vessels, Bharadwaja and Jamadagni, operating from the Malpe Fishing Harbour, Karnataka. Each vessel measured 24 m in overall length and was powered by a 350 HP marine diesel engine. The vessels were designed for extended offshore operations and had a fish hold capacity of 40 t, enabling them to sustain multiday fishing trips in deeper waters. To facilitate efficient mesopelagic fishing and data collection, both vessels were outfitted with modern navigation (Sunhang SH-788A marine navigator), fish detection (Hondex He-775-di Echo Sounder), and communication systems (Satellite phone). These included an advanced echosounder for detecting fish schools and profiling water column characteristics, a Vessel Monitoring System (VMS) for real-time tracking and regulatory compliance, an underwater camera system to document fish behaviour and validate species identification, and a wireless satellite communication system to ensure continuous connectivity during offshore operations.

Typically, the trawlers used by local boat owners operate at depths of around 200 m. For this study, these vessels were specially modified to enable trawling in much deeper waters, reaching depths between 800 and 1000 m. For targeting mesopelagic resources, a specially designed midwater trawl net was employed. This gear was selected to sample fish assemblages occurring within the mesopelagic depth zone (approximately 200–1000 m), enabling the effective capture of mesopelagic species such as myctophids

(lanternfishes) and other ecologically important taxa that exhibit diel vertical migration. The gear was equipped with a headline measuring 70 m and a footline of 78 m, providing an expansive vertical opening for effective operation. The net featured a mesh size of 45 mm throughout the body, tapering down to a codend mesh size of 20 mm. The gear design enabled appropriate vertical opening and stability for efficient midwater trawling.

## Fishing operations

The fishing operations were predominantly conducted during night hours to effectively target diel vertical migrators, species that ascend to the upper water column after dusk and descend to deeper layers during the day. This temporal strategy was adopted to optimise the capture efficiency of mesopelagic species, which are known to exhibit distinct nocturnal vertical movements. During each operation, the midwater trawl was towed at a consistent speed ranging between 2.5 and 3.0 knots. The warp length deployed during trawling was maintained three times the operational depth, with each haul lasting approximately 120 to 180 min, depending on operating depth and prevailing oceanographic conditions. In total, seventeen hauls were executed across twelve designated sampling stations within the study area.

Comprehensive operational data were recorded for each haul to facilitate subsequent analysis. These included precise GPS coordinates of net deployment and retrieval, time of shooting and hauling, towing duration, speed, and the corresponding depth of operation. This detailed documentation was essential for correlating catch composition with spatial and temporal fishing parameters and for assessing gear performance under varying oceanic conditions.

## Environmental parameters

Surface water was collected during the shooting of net and during the towing of net. Sea surface temperature (SST) was measured onboard immediately after collection using a handheld thermometer. The water samples were stored in cans and transported to ICAR-CMFRI, Mangalore Regional Centre Laboratory, where pH, salinity (sal), and TDS were assessed using a multiparameter water quality meter (Horiba U-50). Water samples collected for the analysis of dissolved orthophosphate ( $\text{PO}_4\text{-P}$ ), silicate ( $\text{SiO}_3\text{-Si}$ ), nitrate ( $\text{NO}_3\text{-N}$ ) and nitrite ( $\text{NO}_2\text{-N}$ ), were preserved onboard and analysed following standard analytical methods (APHA, 2022). Chlorophyll *a* (Chl-*a*) concentration was determined by extracting phytoplankton pigments from seawater samples using 90% acetone, following the method of Strickland and Parsons (1972).

## Catch processing and species identification

The fish catch from each haul was immediately sorted and segregated onboard by species to ensure accurate post-capture processing. To maintain freshness and preserve quality, the sorted specimens were stored in the fish hold using a 1:1 ice-to-fish ratio and maintained under chilled conditions for the entire duration of the voyage. Upon completion of the fishing trials, representative portions of the catch landed at Malpe Fishing Harbour were transported under

iced conditions to the Regional Centre of the ICAR–Central Marine Fisheries Research Institute (ICAR-CMFRI), Mangalore for detailed biological studies, including species identification, morphometric measurements, and reproductive assessment. The remaining portion of the catch was carefully packed in ice and transported to the ICAR–Central Institute of Fisheries Technology (ICAR-CIFT), Kochi for proximate composition and biochemical analyses. Species identification was carried out to the lowest possible taxonomic level using taxonomic keys (Venmathi, 2021; Mostarda, 2023). Each specimen was measured for total length and body weight using a standard measuring board and a precision digital balance. Measurements were recorded to the nearest 0.1 cm and 0.1 g, respectively, to ensure accuracy. Subsamples for food and feeding studies were preserved in formalin or ethanol for further analysis.

## Biomass and composition analysis

The total catch from each haul was weighed separately, and catch per unit effort (CPUE) was calculated as  $\text{kg h}^{-1}$ . Species diversity and size distribution of the catch were determined for each haul.

## Participatory framework and stakeholder involvement

This initiative marked the first attempt at the commercial exploitation of mesopelagic resources in the region through a participatory approach that actively engaged fishers, boat owners, and industry stakeholders. The study was designed and implemented using a structured participatory framework that actively integrated multiple stakeholders across all stages of the research process, including planning, execution, and evaluation. The framework involved research scientists, commercial fishers, boat owners, fishing gear manufacturers, and representatives from the fish processing industry, ensuring both scientific rigour and operational relevance. Stakeholder selection was based on predefined criteria, including (i) experience in mesopelagic or offshore fishing, (ii) willingness to participate in experimental trials, (iii) availability of suitable vessels and infrastructure, and (iv) capacity to contribute to post-harvest handling and processing. Commercial trawl vessels were identified through consultations with local fishing associations, and boat owners voluntarily participated in the trials. The initial fishing trials resulted in disappointment for some fishers due to low catches; however, regular interactions with researchers and improvements in fishing operations encouraged their continued participation. Industry stakeholders capable of utilising the catch for further processing for value addition were also involved.

A series of pre-survey consultations and orientation sessions was conducted to align scientific objectives with stakeholder expectations. During these interactions, fishers contributed traditional ecological knowledge (TEK), which informed decisions on potential fishing grounds, depth stratification, diel timing of operations, and gear deployment strategies. Their experiential knowledge was particularly valuable in identifying productive zones and optimising towing practices under dynamic oceanographic conditions.

Fishing operations were carried out collaboratively onboard commercial vessels, with fishers actively involved in gear handling, deployment, and retrieval. Continuous feedback mechanisms were established, allowing real-time adjustments in towing speed,

depth, and gear configuration. Gear manufacturers contributed to modifications such as the incorporation of Ethylene Vinyl Acetate (EVA) floats to enhance performance under mesopelagic pressure conditions. Post-harvest stakeholders, including representatives from the fish processing industry, participated in evaluating catch quality, handling protocols, and value chain potential. Their inputs helped assess the feasibility of processing mesopelagic species for fishmeal, nutraceuticals, and other industrial applications. Researchers ensured systematic data collection, including biological sampling, environmental monitoring, and catch documentation, while integrating stakeholder feedback throughout the study. This collaborative approach facilitated the co-production of knowledge and improved the applicability of scientific outcomes to real-world fisheries development. Fig. 1. depicts a flow chart of the PPP mode of operation for the commercial exploitation of mesopelagic resources.

## Results and discussion

### Fishing effort and operational performance

The mesopelagic fishing operations conducted along the Karnataka coast, covered a depth range of 300 to 800 m (Fig. 2). A total of four mesopelagic trawling expeditions were conducted during the pre-monsoon season, between January and May. The initial voyage faced several technical challenges, resulting in an early termination within two days. However, the subsequent operations were more successful, with each trip lasting between five to six days, demonstrating improved operational efficiency and increasing familiarity with mesopelagic fishing practices. During the first operation, critical equipment failures were observed, including the snapping of the winch wire and the crushing of traditional

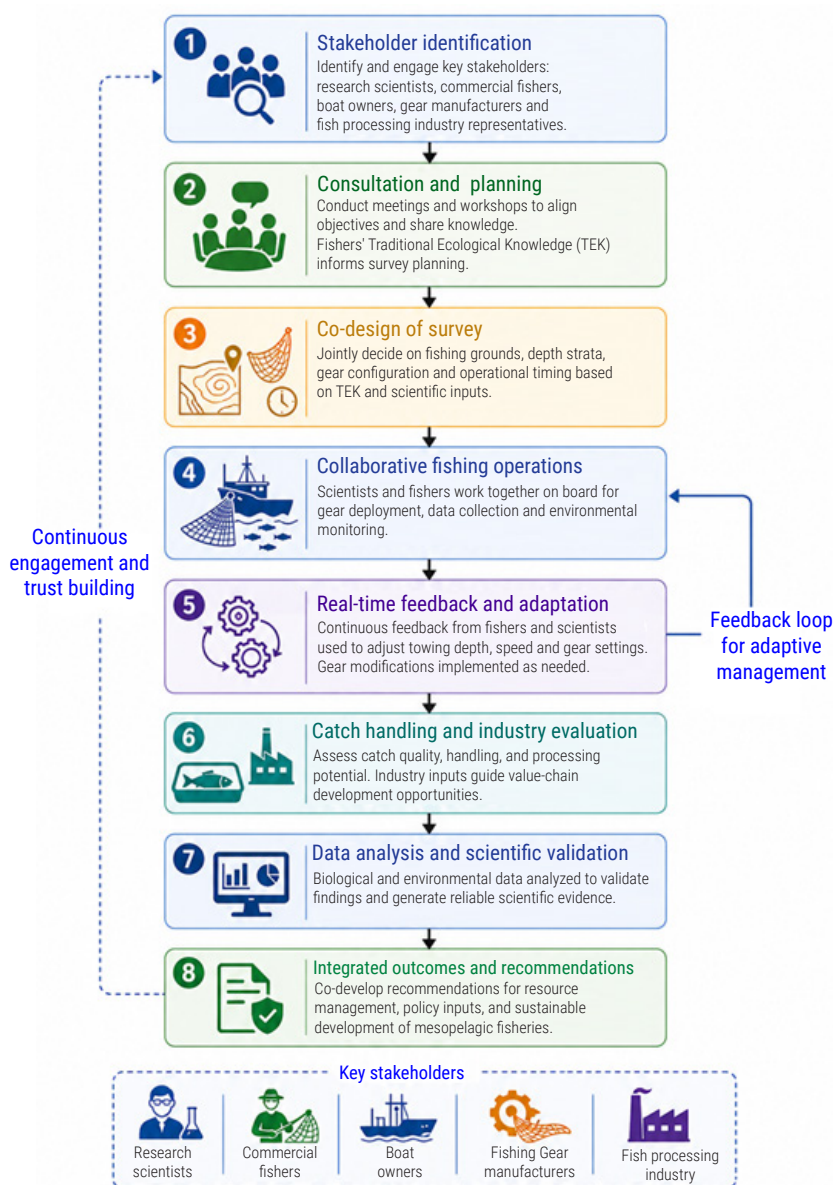


Fig. 1. Flow chart showing the proposed PPP mode of operation for the commercial exploitation of mesopelagic resources

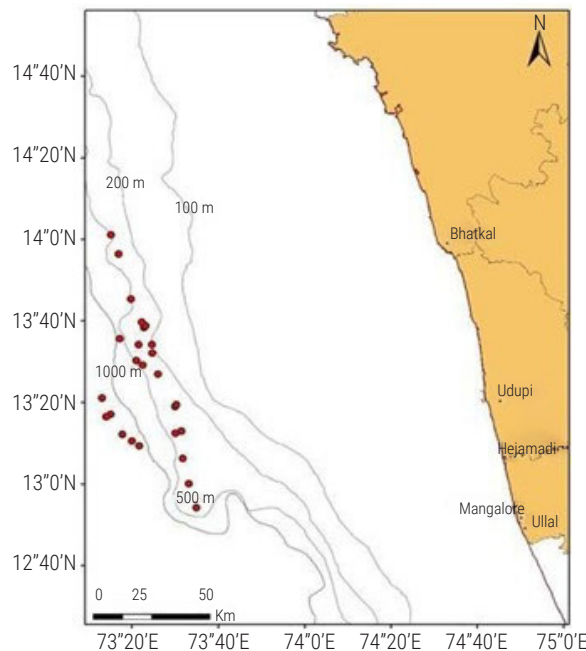


Fig. 2. Map showing the location of the study area

trawl floats due to the intense water pressure encountered at extreme depths. The research team undertook prompt interventions to address these challenges. Modifications included not only strengthening and extending the length of the steel winch wires to accommodate the increased depth, but also addressing equipment failures encountered during the initial trial.

One significant improvement was the replacement of conventional floats with those made from Ethylene Vinyl Acetate (EVA). These EVA floats exhibited superior properties, including light weight, exceptionally high tensile strength, and zero water absorption. Additionally, their remarkable elasticity endowed them with exceptional resistance to shrinkage, permanent deformation, and breakage under the extreme conditions of mesopelagic trawling. This modification substantially enhanced the operational reliability of the trawling system, enabling the successful completion of the deep-water fishing expeditions. Collaborative fishing operations using local vessels demonstrated that with minor modifications, existing trawlers can operate effectively at mesopelagic depths. Fishers' practical knowledge was instrumental in fine tuning towing speeds and depths in response to real time conditions.

During the study, 15 successful hauls were conducted over 156 fishing days, with trawling operations executed at a mean depth of

550 m and a mean towing time of 18060 min per each haul. Table .1 depicts the summary of the sampling efforts in the study.

## Catch composition

A total of 15 successful hauls yielded a combined catch of 4500 kg. The average catch per haul was 360 kg, while the average catch per trial was 1.8 t. CPUE was calculated as the ratio of total towing time (45 h), resulting in an overall CPUE of 120 kg h<sup>-1</sup>. A total of 40 species representing 38 families and 20 orders were recorded during the mesopelagic fishing operations. The species composition reflected considerable taxonomic and ecological diversity. The most represented families are Ophidiidae (23.32%), Pentanchidae (15.94%), and Trachichthyidae (15.05%), each with multiple species captured. Other notable families include Chaunacidae, Moridae, Carapidae, and Nettastomatidae. Monthly mean CPUE ( $\pm$ SD) was 67.2 $\pm$ 4.0 kg h<sup>-1</sup> in January, 202.1 $\pm$ 73.6 kg h<sup>-1</sup> in April, and 64.2 $\pm$ 29.5 kg h<sup>-1</sup> in May.

The family-wise percentage contribution and catch weight recorded during the study are presented in Table 2 . The catch included species of commercial and ecological significance, such as *Bathyclupea hoskynii* (Bathyclupeidae), *Neoharriotta pinnata* (Rhinochimaeridae),

Table. 1. Summary of sampling effort

| Trial No. | Month   | Sampling dates          | Hauls attempted | Depth range (m) | Tow duration (h per haul) | Tow speed (knots) | Catch (kg) (Mean $\pm$ SD) | CPUE (kg h <sup>-1</sup> ) (Mean $\pm$ SD) |
|-----------|---------|-------------------------|-----------------|-----------------|---------------------------|-------------------|----------------------------|--------------------------------------------|
| 1         | January | 20.01.2025 - 24.01.2025 | 5               | 300-600         | 3                         | 2.5-3.0           | 500.0 $\pm$ 113.1          | 67.2 $\pm$ 4.0                             |
| 2         | April   | 16.04.2025 - 20.04.2025 | 5               | 300-800         | 3                         | 2.5-3.0           | 1750.0 $\pm$ 1838.5        | 202.1 $\pm$ 73.6                           |
| 3         | May     | 12.05.2025 - 16.05.2025 | 5               | 300-800         | 3                         | 2.5-3.0           | 450.0 $\pm$ 84.9           | 64.2 $\pm$ 29.5                            |

*Benthoosema fibulatum* (Myctophidae), and *Hoplostethus druzhinini* (Trachichthyidae). Notably, some deep-water cephalopods, such as *Ancistrocheirus lesueurii* (Ancistrocheiridae) and *Sthenoteuthis oualaniensis* (Ommastrephidae), were also recorded, indicating the broad diversity of the sampled ecosystem, which is depicted in Fig. 3.

Table 2. Family-wise percentage contribution and catch weight recorded during the study

| Family            | (%)   | Weight (kg) |
|-------------------|-------|-------------|
| Rhinochimaeridae  | 0.51  | 27.5        |
| Pentanchidae      | 15.94 | 860.8       |
| Echinorhinidae    | 5.34  | 288.3       |
| Ophidiidae        | 23.32 | 1259.3      |
| Trachichthyidae   | 15.05 | 812.7       |
| Chaunacidae       | 8.26  | 446.0       |
| Moridae           | 7.86  | 424.4       |
| Carapidae         | 6.78  | 366.1       |
| Nettastomatidae   | 6.66  | 359.6       |
| Bembropidae       | 0.91  | 49.1        |
| Anguillidae       | 0.87  | 46.9        |
| Nemichthyidae     | 0.84  | 45.3        |
| Congridae         | 0.83  | 44.8        |
| Bothidae          | 0.70  | 37.8        |
| Lophiidae         | 0.68  | 36.7        |
| Centrolophidae    | 0.54  | 29.1        |
| Gempylidae        | 0.42  | 22.6        |
| Alepocephalidae   | 0.33  | 17.8        |
| Synagropidae      | 0.24  | 12.9        |
| Myctophidae       | 0.17  | 9.1         |
| Muraenesocidae    | 0.16  | 8.6         |
| Colocongridae     | 0.10  | 5.4         |
| Nomeidae          | 0.08  | 4.3         |
| Setarchidae       | 0.08  | 4.3         |
| Stomiidae         | 0.08  | 4.3         |
| Evermannellidae   | 0.07  | 3.7         |
| Macrouridae       | 0.07  | 3.7         |
| Synodontidae      | 0.06  | 3.2         |
| Chlorophthalmidae | 0.05  | 2.7         |
| Bathyclupeidae    | 0.04  | 2.1         |
| Notacanthidae     | 0.02  | 1.0         |
| Nephropidae       | 0.11  | 5.9         |
| Aristeidae        | 0.07  | 3.7         |
| Acanthephyridae   | 0.06  | 3.2         |
| Ancistrocheiridae | 0.69  | 37.2        |
| Ommastrephidae    | 0.20  | 10.8        |
| Periphyllidae     | 1.14  | 61.5        |
| Atollidae         | 0.68  | 36.7        |

### Occurrence and size distribution

Among the 40 species recorded during the trials, 12 species viz., *N. pinnata*, *B. fibulatum*, *Bythaelurus hispidus*, *Chaunax multilepis*, *H. druzhinini*, *Nemichthys scolopaceus*, *Nettastoma parviceps*, *Physiculus indicus*, *Aristeus alcocki*, *Nephropsis stewarti*, *Atolla wyvillei* and *Periphylla periphylla* were constantly observed in all three trial operations. The occurrence of major species in different trials is depicted in Table 3.

### Environmental observations

Surface water temperature ranged from 28.15 to 30.34°C, with an average of 29.9°C. The mean concentrations of dissolved nutrients



Fig. 3. Major orders, families, and species recorded during the sampling period

Table 3. Occurrence of mesopelagic species in different fishing trials

| Species                             | Trial 1 | Trial 2 | Trial 3 |
|-------------------------------------|---------|---------|---------|
| <i>Neoharriotta pinnata</i>         | ✓       | ✓       | ✓       |
| <i>Echinorhinus brucus</i>          | X       | ✓       | X       |
| <i>Benthoosema fibulatum</i>        | ✓       | ✓       | ✓       |
| <i>Alepocephalus blanfordii</i>     | X       | X       | ✓       |
| <i>Bathyclupea hoskynii</i>         | X       | X       | ✓       |
| <i>Bembrops platyrhynchus</i>       | X       | ✓       | ✓       |
| <i>Bythaelurus hispidus</i>         | ✓       | ✓       | ✓       |
| <i>Chascanopsetta lugubris</i>      | ✓       | X       | ✓       |
| <i>Chauliodus sloani</i>            | X       | X       | ✓       |
| <i>Chaunax multilepis</i>           | ✓       | ✓       | ✓       |
| <i>Chlorophthalmus corniger</i>     | X       | X       | ✓       |
| <i>Coccorella atrata</i>            | X       | X       | ✓       |
| <i>Congrhynechus talabonoides</i>   | ✓       | ✓       | ✓       |
| <i>Coryphaenoides sp.</i>           | X       | X       | ✓       |
| <i>Cubiceps pauciradiatus</i>       | X       | X       | ✓       |
| <i>Dicrolene multifilis</i>         | ✓       | X       | ✓       |
| <i>Harpadon nudus</i>               | X       | X       | ✓       |
| <i>Hoplostethus druzhinini</i>      | ✓       | ✓       | ✓       |
| <i>Hypopleuron caninum</i>          | X       | ✓       | ✓       |
| <i>Lophiodon mutilus</i>            | X       | ✓       | ✓       |
| <i>Lythrichthys longimanus</i>      | X       | X       | ✓       |
| <i>Nemichthys scolopaceus</i>       | ✓       | ✓       | ✓       |
| <i>Neopinnula orientalis</i>        | X       | X       | ✓       |
| <i>Nettastoma parviceps</i>         | ✓       | ✓       | ✓       |
| <i>Notacanthus indicus</i>          | X       | X       | ✓       |
| <i>Parascombrops pellucidus</i>     | X       | X       | ✓       |
| <i>Physiculus indicus</i>           | ✓       | ✓       | ✓       |
| <i>Psenopsis intermedia</i>         | X       | ✓       | ✓       |
| <i>Pycnocraspedum squamipinne</i>   | ✓       | X       | ✓       |
| <i>Sauromuraenesox vorax</i>        | X       | X       | ✓       |
| <i>Acanthephyra sibogae</i>         | X       | ✓       | ✓       |
| <i>Aristeus alcocki</i>             | ✓       | ✓       | ✓       |
| <i>Glyphocrangon investigatoris</i> | ✓       | X       | X       |
| <i>Nephropsis stewarti</i>          | ✓       | ✓       | ✓       |
| <i>Ancistrocheirus lesueurii</i>    | X       | X       | ✓       |
| <i>Sthenoteuthis oualaniensis</i>   | ✓       | X       | X       |
| <i>Atolla wyvillei</i>              | ✓       | ✓       | ✓       |
| <i>Periphylla periphylla</i>        | ✓       | ✓       | ✓       |

were 0.005714286 mg l<sup>-1</sup>, 0.132676471 mg l<sup>-1</sup>, 0.027145176 mg l<sup>-1</sup>, 0.009231 mg l<sup>-1</sup> for PO<sub>4</sub>-P, SiO<sub>3</sub>-Si, NO<sub>3</sub>-N and NO<sub>2</sub>-N, respectively. The mean productivity in terms of Chlorophyll a concentration was 0.02 mg m<sup>-3</sup>.

## Bycatch and ecosystem observations

Gelatinous zooplankton, represented primarily by *Periphylla periphylla* and *Atolla* cf. *wyvillei*, constituted a recurrent component of the trawl bycatch across depths of 300–800 m, accounting for 1.82% of the total recorded fauna. Although their overall contribution to the catch was low relative to commercially important fishes, jellyfish occurrence was significant in certain hauls. In some instances, particularly during early morning and evening trawls, gelatinous zooplankton dominated or constituted nearly the entire catch. Such episodic aggregations may interfere with trawl operations and gear performance, while increasing the proportion of non-commercial bycatch, thereby reducing the efficiency of targeted fishing operations. No protected or threatened species were recorded during the surveys; however, this observation should be interpreted cautiously, given the limited spatial and temporal extent of sampling in the present study.

## Discussion

The preliminary trials conducted off the Karnataka coast mark a pivotal first step in understanding and tapping the mesopelagic fishery potential within the Indian EEZ. Uniquely structured as a participatory initiative, these efforts directly engaged local fishers, boat owners, and industry partners, creating an essential bridge between scientific exploration and operational reality. This inclusive framework not only enhanced the trials' practical relevance but also enabled a faster feedback loop for adapting technologies and strategies. This study represents the first commercial scale, participatory effort to explore mesopelagic and upper bathypelagic resources along the Karnataka coast, reaching depths of up to 800 m. These depths go far beyond the conventional 200 m typically exploited by local fleets (Sinha *et al.*, 2017), and the successful deployment of modified traditional vessels confirmed the operational feasibility of mesopelagic expeditions. Notably, the incorporation of EVA floats and reinforced fishing gear enabled the vessels to overcome the high-pressure conditions, representing a practical gear innovation in line with the recommendations from previous works (Boopendranath *et al.*, 2012b; Castellon and Olivar, 2023).

Despite these advancements, several operational hurdles surfaced during the study. Equipment failures, particularly float collapse and winch wire damage, highlighted the technical setbacks associated with deep-sea fishing operations. The successful adaptation of high-tensile floats, upgraded winches, and synthetic gear helped overcome these constraints, demonstrating the critical role of gear innovation in expanding deep-sea fishing capabilities. Direct input from experienced onboard crews proved equally vital, as real-time adjustments in towing speed and trawl deployment guided by local knowledge contributed significantly to the successful execution of the fishing trials.

The species composition recorded during the fishing trials comprised 40 species, representing 38 families and 20 orders. Dominant

groups included Ophidiidae, Pentanchidae, and Trachichthyidae, along with frequent catches of Myctophidae (e.g., *B. fibulatum*). These findings are consistent with earlier observations from the Indian EEZ (Jayaprakash, 1996; Sajeevan *et al.*, 2009; Vipin *et al.*, 2012), highlighting the prevalence of myctophids and other mesopelagic taxa. Noteworthy occurrences of *Hoplostethus* sp., *N. pinnata*, and *B. hispidus* reinforce the continued presence of these taxa in the Indian deep-sea ecosystems (Venu and Kurup, 2002).

Catch rates averaged 120 kg h<sup>-1</sup> with a biomass of approximately 1.8 t per trip. These numbers compare favourably with prior exploratory efforts in the Indian EEZ, where catch rates ranged from 18 to 1185 kg h<sup>-1</sup> depending on latitude and depth (Venu and Kurup, 2002). Various mesopelagic fishing studies in other oceanic zones have shown inconsistent catch rates. Experimental trawling operations in the Gulf of Oman targeting mesopelagic resources recorded daily catches of 20 to 28 t, primarily consisting of myctophids and other lanternfish (Valinassab *et al.*, 2007). Exploring myctophid resource studies conducted in the Arabian Sea showed catch rates of an estimated 62.1 kg during targeted midwater trawling operations (Boopendranath *et al.*, 2012a). Although catch rates varied significantly depending on gear configuration, depth strata, and oceanographic conditions, studies from the Pacific Ocean have also reported high mesopelagic biomass and commercially exploitable catch potentials, especially for lanternfish dominated assemblages (Gjosæter and Kawaguchi, 1980; Irigoien *et al.*, 2014).

Particularly encouraging was the substantial catch at a mean depth of 550 m, suggesting that Karnataka's deep shelf-slope zone holds strong mesopelagic resource potential. The high species diversity and promising biomass observed in this study align with previous reports stating that the Arabian Sea possesses high biodiversity and fish biomass in its mesopelagic zone (Bucklin *et al.*, 2024). In addition, the global biomass estimates indicate that mesopelagic fish resources could be between 495 and 987 million t, showing their significant potential for fisheries (Pauly *et al.*, 2021). Another significant observation was the broad size range recorded for several key species such as *Nemichthys scolopaceus* (172–810 mm; Table 4) and *Sauromuraenesox vorax* (up to 630 mm). The wide size distribution indicates that these waters may provide diverse habitats supporting different life stages and ecological functions including growth and feeding. Such size related habitat use is consistent with patterns reported for deep-sea fish assemblages in the Indian region (Sajeevan *et al.*, 2009).

The feasibility of mesopelagic resource exploitation in the present study area was critically evaluated by comparing the observed catch rates with those reported from other regions of the Indian Ocean. The overall CPUE recorded during the present trials (~120 kg h<sup>-1</sup>) is comparatively lower than values reported from certain exploratory and commercial scale operations in other parts of the Indian Ocean, where higher catch rates have been documented (e.g., Valinassab *et al.*, 2007; Boopendranath *et al.*, 2012a). However, it is important to note that the present study represents an initial exploratory effort with limited spatial coverage and a relatively small number of hauls (n=15), which may not adequately capture the spatial heterogeneity and patchy distribution typical of mesopelagic resources. Furthermore, the primary objective of the trials was to assess operational feasibility and gear performance under participatory conditions rather than to optimise catch efficiency.

Table 4. Length range of major species recorded from different fishing areas

| Species                           | Common name                | Length range (mm) |
|-----------------------------------|----------------------------|-------------------|
| <i>Bathyclupea hoskynii</i>       | Indian deep-sea herring    | 186               |
| <i>Parascombrops Pellucidus</i>   | Aden splitfin              | 73                |
| <i>Alepocephalus banfordii</i>    | Slickheads                 | 115-133           |
| <i>Congrhynchus talabonoides</i>  | Indian pike conger         | 203-500           |
| <i>Sauromuraenesox vorax</i>      | Pike conger                | 376-630           |
| <i>Nettastoma parviceps</i>       | Duck-billed eel            | 136-643           |
| <i>Nemichthys scolopaceus</i>     | Slender snipe eel          | 172-810           |
| <i>Coccorella atrata</i>          | Sabertooth fish            | 89-117            |
| <i>Harpadon nudus</i>             | Deepsea Bombay duck        | 195               |
| <i>Chlorophthalmus corniger</i>   | Spinyjaw greeneye          | 114-126           |
| <i>Bythaelurus hispidus</i>       | Bristly catshark           | 211-365           |
| <i>Neoharriotta pinnata</i>       | Sicklefin chimaera         | 129-403           |
| <i>Echinorhinus brucus</i>        | Bramble shark              | 734-804           |
| <i>Coryphaenoides sp.</i>         | Rattail                    | 16.2-185          |
| <i>Physiculus indicus</i>         | Indian cod                 | 153-250           |
| <i>Chaunax multilepis</i>         | Indian spotted coffinfish  | 126-211           |
| <i>Lophiodes mutilus</i>          | Smooth angler              | 175-293           |
| <i>Benthoosema fibulatum</i>      | Spinycheek lanternfish     | 35-75             |
| <i>Notacanthus indicus</i>        | Indian spiny-back eel      | 103-226           |
| <i>Hypopleuron caninum</i>        | Whiptail cusk              | 166-641           |
| <i>Dicrolene multifilis</i>       | Slender brotula            | 111-188           |
| <i>Pycnocraspedum squamipinne</i> | Pelagic cusk               | 184-350           |
| <i>Bembrops platyrhynchus</i>     | Natal duckbill             | 131-208           |
| <i>Lythrichthys longimanus</i>    | Red deepwater scorpionfish | 112               |
| <i>Chascanopsetta lugubris</i>    | Pelican flounder           | 296-327           |
| <i>Psenopsis intermedia</i>       | Medusa fish                | 122-250           |
| <i>Cubiceps pauciradiatus</i>     | Bigeye cigarfish           | 145               |
| <i>Chauliodus sloani</i>          | Sloane's viperfish         | 214-232           |
| <i>Hoplostethus druzhinini</i>    | Slimehead                  | 81-170            |

A comparative analysis of CPUE values from different studies has been included in Table 5, to contextualise the observed differences. Based on the current results, it is acknowledged that the catch rates obtained are below thresholds generally considered commercially viable. Nevertheless, there is potential for improvement through targeted refinement of fishing strategies, including better identification of resource rich zones, optimisation of towing depth and timing, and further gear modifications. Therefore, while the present findings indicate that large scale commercial viability in the study area remains uncertain at this stage, they also highlight the need for more extensive, multi season and multi-location exploratory trials to arrive at a conclusive assessment.

The trials also revealed a striking abundance of gelatinous zooplankton in the bycatch, including species such as *P. periphylla* and *A. wyvillei*. This gelatinous dominance posed operational difficulties, often clogging nets and increasing sorting time, while also prompting ecological questions about trophic interactions, gear selectivity, and long-term ecosystem impacts (Grimaldo *et al.*, 2022). These challenges underline the urgent need for selectivity improvements in gear design and ecosystem-based management approaches. Importantly, no sea turtle, marine mammals, elasmobranchs, or other species listed under the Wildlife (Protection) Act, 1972 were recorded in the exploratory hauls during the study period. Although this observation provides useful baseline information on the non-target catch, the limited spatial and temporal coverage of the trials does not permit conclusions regarding the potential interaction of mesopelagic fishing with threatened or protected fauna. Nonetheless, jellyfish dominated hauls underscore the potential interference of mesopelagic fishing with non-commercial species.

The physico-chemical characteristics of the mesopelagic zone, including low chlorophyll *a* concentrations and relatively low nutrient levels, reflect the environmental conditions that influence the distribution and composition of mesopelagic fauna. These conditions are consistent with those reported for the mesopelagic region of the Indian Ocean (Vipin *et al.*, 2012), and are associated with distinct ecological and physiological adaptations among mesopelagic species. Surface water parameters may not adequately represent the environmental conditions prevailing in the mesopelagic fishing depths (300–800 m). This represents a limitation of the current exploratory study, as the participating commercial vessels were not equipped with instruments for *in situ* deep-water sampling such as CTD rosettes. However, surface measurements provide useful baseline oceanographic information for the study area.

Post-harvest handling emerged as a critical operational bottleneck during the trials. Many of the target species were fragile and highly perishable, with quality deteriorating quickly in the absence of adequate chilling. The conventional fishing vessels used in the trials lacked adequate cold storage or freezing facilities, resulting in post-harvest quality losses and reduced the commercial value of the catch (Boopendranath, 2007). To address this, selected vessels were retrofitted with insulated fish holds and ice slurry chilling systems, which helped improve the preservation and handling of

Table 5. Comparison of catch per unit effort (CPUE) of mesopelagic resources from different regions of the Indian Ocean

| Region/Area                              | Depth range (m) | Gear type      | CPUE (kg h <sup>-1</sup> ) | Remarks                                                   | Reference                           |
|------------------------------------------|-----------------|----------------|----------------------------|-----------------------------------------------------------|-------------------------------------|
| Karnataka coast (Present study)          | 200–800         | Midwater trawl | ~120                       | Exploratory trials; limited hauls; participatory approach | Present study                       |
| South-west coast of India (Arabian Sea)  | 200–1000        | Midwater trawl | 18–1185                    | Wide variation depending on depth and location            | Venu and Kurup (2002)               |
| Arabian Sea (CIFT exploratory trials)    | 200–1000        | Midwater trawl | ~200–800                   | Experimental trials with gear standardisation             | Boopendranath <i>et al.</i> (2012b) |
| Oman Sea (Western Indian Ocean)          | 300–600         | Midwater trawl | ~833–1167*                 | High biomass zones; commercial scale trials               | Valinassab <i>et al.</i> (2007)     |
| Western Indian Ocean (General estimates) | 200–1000        | Midwater trawl | Variable                   | High biomass; spatially patchy distribution               | Lam and Pauly (2005)                |
| Indian EEZ (DSL surveys)                 | 200–1000        | IKMT/Trawl     | Variable                   | Strong spatial and temporal variability                   | Karuppasamy <i>et al.</i> (2010)    |

CPUE values are indicative and may vary depending on gear configuration, sampling strategy, and environmental conditions.

\*Converted from reported catch rates of 20–28 t day<sup>-1</sup>.

species with limited shelf life (Shawyer and Pizzali, 2003). Additional operational challenges included gear entanglement associated with complex seabed terrain and interference from dense aggregations of gelatinous organisms. These recurring operational difficulties point to the need for purpose designed fishing gear and onboard systems optimised for mesopelagic fishing conditions. Strengthening the cold chain infrastructure and improving onboard handling and processing capabilities will also be crucial for maintaining catch quality and ensuring economic viability of mesopelagic fisheries.

Ecologically, mesopelagic species play central roles in marine food webs and global biogeochemical cycles, particularly through their contribution to the oceanic biological carbon pump (Suuronen *et al.*, 2018; FAO, 2022). Mesopelagic fishes and associated micronekton are central to the biological carbon pump, actively transporting carbon from surface waters to the deep ocean through diel vertical migration, respiration, and production of fast sinking faecal pellets, thereby contributing to long term carbon sequestration (Oostdijk *et al.*, 2024; World Bank, 2024). Recent studies highlight that mesopelagic fishes constitute a vital but poorly understood component of this process, with substantial uncertainties regarding how their removal may influence climate regulation and carbon fluxes (Oostdijk *et al.*, 2024). In addition to their biogeochemical role, mesopelagic organisms form a crucial trophic link, serving as a primary prey base for higher trophic-level predators such as tunas, billfishes, marine mammals, and seabirds, thereby sustaining pelagic food webs and commercially important fisheries (Weir *et al.*, 2025). Large-scale biomass extraction from this layer may therefore trigger cascading ecological effects, altering predator-prey dynamics and ecosystem stability. Furthermore, disruption of diel vertical migration patterns could interfere with nutrient recycling processes and midwater ecosystem functioning, with broader implications for ocean productivity and biogeochemical cycling (Weir *et al.*, 2025). Thus, their exploitation must be carefully managed to prevent cascading effects on ecosystem processes, which necessitates regular stock assessments, adaptive catch limits, and potentially spatial protections.

Given these ecological uncertainties and potential trade-offs between provisioning and regulating ecosystem services, there is a growing consensus on adopting a precautionary approach for the development of mesopelagic fisheries. Recent assessments emphasise that exploitation of mesopelagic resources, even at sustainable yield levels, may result in losses to ecosystem services, including carbon sequestration and trophic support, underscoring the need for cautious and adaptive management (Sadik-Zada *et al.*, 2023; Prellezo *et al.*, 2024). In this context, international advisory bodies such as the International Council for the Exploration of the Sea (ICES) advocate ecosystem-based management, improved understanding of mesopelagic ecosystem functioning, and the implementation of conservative harvest strategies in the absence of robust stock and ecosystem assessments (ICES, 2023, 2024). Accordingly, the present study emphasises the need for comprehensive environmental impact assessments, long term monitoring of ecosystem responses, and integration of ecological considerations into fisheries development frameworks. A precautionary and ecosystem-based approach will be essential to ensure that the emerging mesopelagic fishery contributes to food security and the blue economy without compromising critical ecosystem functions.

A key feature of the present study was its participatory approach. The involvement of local stakeholders ensured that the research remained grounded in economic and practical realities while fostering greater buy-in and knowledge exchange. The rapid problem solving during the trials enabled by crew experience and iterative feedback validates the participatory model as an effective strategy for developing emerging fisheries. Looking ahead, maintaining and expanding this collaborative framework is essential. It will support adaptive management, informed policy development, and equitable benefit sharing. As mesopelagic fisheries move from exploratory stages toward commercial development, local stakeholder engagement will be vital in shaping governance structures and ensuring responsible utilisation.

Significant operational and socioeconomic advantages for exploring mesopelagic fisheries were shown by the participatory framework used in this study. The active participation of fishers, boat owners and industry stakeholders, promoted knowledge sharing, increased trust, and enhanced the acceptance of modified fishing technologies and techniques. Optimising towing operations, lowering trial-and-error efforts, and increasing overall operational efforts were all made possible by the integration of traditional and ecological knowledge (TEK) with scientific survey design, stakeholder engagement and fishing operations. Recognising the experiential knowledge of fishers as an integral part of the research process improved both stakeholder engagement and the practical applications of the fishing operation. The collaborative approach adopted in this study provides an important foundation for future mesopelagic fisheries management in India. Continued engagement among scientists, fishers, and industry stakeholders can support adaptive management, technological improvements and development of region-specific harvesting strategies. Such multi-stakeholder frameworks can also facilitate compliance with regulations, streamline resource management, enable equitable benefit sharing and contribute to the sustainable development of mesopelagic fisheries under the blue economy framework. As interest in mesopelagic resources grows, participatory approaches will be important for balancing resource utilisation with long-term ecosystem sustainability.

In summary, these preliminary trials represent a foundational step towards improving the understanding and assessment of India's mesopelagic fisheries potential. However, the feasibility of large scale commercial exploitation requires further extensive investigation. While the trials demonstrated the adaptability of fishing gear and vessel operations, challenges related to gear performance handling and storage of catch as well as environmental sustainability remain to be addressed. Transitioning towards large scale operations will require continued innovation in fishing gear, enhanced vessel infrastructure, targeted ecological research, and science-informed policy frameworks. An integrated, participatory, and precautionary approach is essential to ensure that any future development of mesopelagic fisheries contribute meaningfully to food security and livelihood diversification, while safeguarding ecosystem functions within India's evolving blue economy.

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