Critical evaluation of India's trawl fisheries: pathways for responsible growth and sectoral harmony

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Mechanised fisheries, led by trawlers, contribute 70%–80% of India's marine fish production, yet the sector's growth must align with the nation's inclusive approach that values the coexistence of mechanised, motorised, and traditional fisheries for sustainable coastal development. The present study critically evaluates the trawl fishery's adherence to best practices, aiming to identify necessary reforms that ensure responsible growth without disrupting sectoral harmony in Indian marine fisheries. Globally, trawl management measures include regulatory actions and voluntary industry initiatives aimed at reducing the environmental effects of trawling, in alignment with broader sustainability goals. These measures cover gear design, trawl operations, spatial controls, impact quotas, and effort controls. The study highlights significant shifts in Indian trawl operations, especially since 2010. Notably, there is an increase in the presence of off-bottom species, while conventional resources like crustaceans decline. Trawlers in India are found to be emitting fewer greenhouse gases for catching 1 kg of fish compared to global trawling standards, and with the majority of India's wild-caught export commodities coming from trawl fisheries, the lower carbon footprint of these operations enhances their appeal in the export market and positions them for carbon trading opportunities. The study also highlights the immediate need to reduce engine power according to vessel size to improve fuel efficiency, and additionally, it is important to identify an optimal fleet size based on resource availability, as the decrease in catch rates is increasing competition among trawler operators. State governments have various legal tools to address unsustainable practices. Although minimum legal size (MLS) restrictions are in place in most maritime states, the high costs associated with their strict enforcement are weakening their effectiveness. From a responsible fishing perspective, fish meal and fish oil plants voluntarily reject commercially caught species below the MLS size. If properly enforced, this approach can help control the possible expansion of high-speed pelagic trawling operations more effectively.

Keywords: Best practices, carbon footprint, gear modification, self-regulation, semi-pelagic trawling, sustainability, trawl fishery

MECHANISED fisheries, primarily driven by trawlers, contribute ~70%–80% of India's marine fish production[1]. Despite this dominance, the coexistence of mechanised, motorised, and traditional (non-mechanised) sectors has been a cornerstone of India's inclusive approach to marine fisheries development. This integration has not only enhanced production and economic growth but also supported livelihood sustainability for millions and contributed to balanced coastal development. Recognising the importance of this delicate balance, Indian marine fisheries policies have historically advocated for a co-existence policy: supporting artisanal fishers while enforcing regulations on industrial operations, particularly trawling. The trawl sector, known globally for its ecological and social impacts, demands constant evaluation and adaptive regulation. International bodies such as the Food and Agriculture Organization (FAO) have repeatedly emphasised the need for responsible trawling practices, issuing best practice guidelines and promoting sustainable gear and methods. Given the high investment nature and resource-intensive character of the mechanised sector, it is the duty of fisheries managers to periodically assess its growth, impacts, and alignment with national goals of equity and sustainability.

Trawl fishing is the predominant fishing method in India, contributing significantly to the marine fish catch in India, ~40%–50% of marine fish production on average during the last decade. In 2022 India's trawl landing was 1.85 million tonnes (t), forming 53% of the total landing[1]. This sector plays a pivotal role in the marine fisheries export from the country. According to the 2016 enumeration, Indian fishers operated a trawler fleet of 30,772 vessels[2], with almost all trawlers measuring less than 20 m in overall length (OAL). Among the 4,945,717 marine fishers and fishery-dependent population in India[3], half of this population relies directly or indirectly on income generated from trawl-fishing-related activities for their livelihoods.

Globally, trawling is acknowledged as one of the more invasive fishing methods, impacting not only target fish populations through the removal of fish and size-selective

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harvesting but also exerting wide-ranging ecosystem effects, including those on benthic organisms, habitats, and non-target species, as noted by Jennings *et al.*[4], and Schratzberger and Jennings[5]. From a carbon footprint perspective, trawling is recognised for releasing sediment-bound carbon dioxide from fuel combustion, as highlighted by Epstein *et al.*[6]. The impact of bottom trawling on the seabed is contingent upon the habitat and the fishing gear employed, as elucidated by Collie *et al.*[7] Recently, concerns have arisen not only regarding carbon emissions from trawl fisheries due to fuel use but also from trawl-induced CO_2 release from the seabed[8].

Specific studies on the increasing crustacean composition in global trawl catch reveal higher greenhouse gas (GHG) and carbon dioxide release, as demonstrated by Boenish *et al.*[9]. Recent research indicates that trawl designs can be modified to reduce contact area without significantly affecting the catch rate of target species, thereby potentially reducing the mortality of escaping animals[10] or minimising fuel consumption[11]. From an Indian perspective, a review of trawl fisheries activities suggests a changing landscape in trawling developments. Vivekanandan[12] reported an emerging dominance of pelagics in the trawl fishery, with the contribution of small and large pelagics jointly increasing in different regions of the Bay of Bengal. Similar trends were observed on the west coast of India, Arabian Sea, as reported by Dineshbabu[13].

In a report submitted to the FAO, the introduction of mid-water trawls was found to increase the contribution of pelagic/column fishes in trawl landings from the Arabian Sea. There was a shift in species preference among trawl operators favouring cephalopods, ribbonfishes, and threadfin breams due to substantial export market demand. To align with changing market demands, adjustments in trawl gear design are deemed imperative for efficiently targeting preferred species.

Amidst international debates on 'the carbon benefits of ending bottom trawling'[14,15] and ecological expenses associated with increasing global crustacean catch[9], a study was conducted to comprehend the distinct characteristics of Indian trawl fisheries. McConnaughey *et al.*[16] highlighted that management measures and voluntary industry initiatives can potentially mitigate trawling impacts, contributing to sustainability goals in fisheries, conservation, and environmental management. Such measures involve modifications in gear design, trawl operation, spatial controls, impact quotas, and effort controls.

The present study provides insights into the efforts within Indian trawling operations to transition from bottom trawling to semi-pelagic trawling, facilitated by advancements in net design and the adoption of high-power engines[13]. While this transformation was primarily demand-driven, globally recognising the reduction of instances of bottom contact is deemed imperative to mitigate the impact of trawling. This is critical, given that the mortality of benthic invertebrates resulting from trawl gears is intricately linked to the extent of gear penetration into the seabed, as highlighted by Hiddink *et al.*[17]. In this context, the Indian trawl fishery is positioned as more ecologically and environmentally friendly according to global standards. The study aims to elucidate changes in terms of species composition and operational modifications in the Indian trawl fishery, emphasising the reduction of ecological impacts.

At the same time, while off-bottom trawling is praised for its low bottom disturbance, the parallel developments involving high investments in fast engines, advanced fish-finding technologies, and quick access to forecast areas provided by state-owned departments are being used by trawl operators in certain parts of the country, which undermines the intended benefits of off-bottom trawling. Recently, the advantages of high-speed engines and customised net designs in the fishery industry have reportedly led to the rise of high-speed pelagic trawling, resulting in large quantities of small-sized fish being caught. This practice violates existing fishing regulations in India, such as minimum legal size, mesh size regulations, and engine speed limits. Fishmeal industries are reportedly the primary buyers of these small fish. Voluntary rejection of these fish by fishmeal industries could help curb these illegal practices. Alternatively, strict monitoring of raw materials used in fishmeal plants, similar to the implementation of the minimum legal size (MLS) regulations, could help improve the reputation of trawl fisheries. This would ensure that good practices in trawling are not overshadowed by such harmful activities.

To comprehend on-field improvisations, information was gathered through structured log sheet data[18] and a questionnaire-based study. Indian trawl landing data over the last four decades, with representative data for the years 1992, 2002, 2012 and 2022, were analysed to underscore evolutionary evidence. After identifying the period of shift in trawling operations, data from the identified period underwent more intensive investigation using case studies from selected, highly significant trawl fishing zones. The carbon footprint of the Indian trawl fishery was also estimated to comprehend its global standing. The present study, therefore, undertakes a critical evaluation of trawl fisheries in India, specifically examining their adherence to best practices in trawling, and identifies potential areas where corrective measures are needed. The goal is to ensure that the mechanised sector, while vital, does not undermine the sectoral harmony that has long sustained India's marine fisheries—and that all subsectors can thrive together within a responsible and inclusive fisheries governance framework.

Material and method

India has a rich variety of fisheries resources in the eastern Arabian Sea and Bay of Bengal, which are divided into four different ecological zones. The ICAR-Central Marine Fisheries Research Institute (CMFRI), Kochi, with over 75 years of experience in collecting marine fisheries data, has one of the most valuable fisheries databases in the world. For this analysis, data from the National Marine Fisheries Data Centre (NMFDC) of CMFRI, collected using standard methods[19], were used. Even though historical data is available, comparing the average data from one decade to the next does not clearly show the extent of changes that occurred over that time. To identify the changes more accurately, years with at least 10 years of difference from 2022 were chosen for the study. For the analysis, trawl fishery data from 1992, 2002, 2012 and 2022 were selected. Catch and effort analysis was done by looking at the proportion of single-day operating trawlers and multi-day operating trawlers, focusing on the number of trawlers and their hours of operation, as well as the catch in each category. Since multi-day trawlers became regular after 2000, CMFRI began separating them into two categories: multi-day trawlers and single-day operating trawlers from 2006 onwards. The data in these categories were analysed to understand their contributions. MS Excel basic calculations were used for the catch analysis, and for better clarity in data presentation, 'Sankey diagrams' are used.

The data were analysed based on the type of fish caught, dividing them into three groups: demersal species (bottom-dwelling fish like finfish and shellfish), column species (which move freely between the bottom and surface), and pelagic fish (which live near the surface). This classification was based on how the species are found in the fishery, regardless of their scientific classification. On the national scale, from the landing data, classification of species in the landing according to their 'niche preference' was the only direct proof for changes in trawl operations. Species were classified based on their occurrence, published information on habitat preferences, and corroborative inputs from fishers drawing on their practical experience and local ecological knowledge. The classification scheme adopted in the present study is shown in Table 1.

Field-level data collection using Marine Citizen Science concept

To understand the changes in the trawl fishery in terms of fishing operations, fishing grounds, target species, and bycatch, as well as to gather the perceptions of fishery stakeholders, 50 structured questionnaires were filled out by scientists during visits to fishing centres in Veraval, Mumbai, Mangaluru, Kochi, Tuticorin, Chennai, Visakhapatnam, Puri, and Digha.

India does not have a mandatory system for keeping logs on fishing vessels, and most fishing information is treated as intellectual property. So far, there is no state-level system to monitor spatial fishing data. To collect information on where fishing happens, what species are caught, and how nets are used over time and space, customised programmes were developed[18].

Some parts of the study required close coordination with trawl fishers and support from fishing harbours. In many cases, fishers voluntarily shared information, which helped in analysing the changes in trawl fisheries in detail. Participatory research programmes were also organised regularly throughout the year. At the fishing harbours in Mangaluru (on the southwest coast) and Veraval (on the northwest coast), progressive fishers have been voluntarily providing continuous data on fishing activities, fish species, and net usage. This valuable data from Veraval and Mangaluru was used to study how trawl fisheries have developed based on fishing grounds.

Regional studies use of different nets in trawling operations

It is well known that modern trawlers carry more than one type of net, allowing them to target different resources based on availability in the fishing grounds. The decision to use special types of gear for different resources depends on the crew's skill in identifying fish shoals, and this knowledge is considered their intellectual property. Gathering national-level data on such skilled operations is difficult. However, with the cooperation of progressive fishers who agreed to share data on board, an analysis was conducted on the proportion of bottom and off-bottom fisheries along the Gujarat coast, the northeast coast of India and the Mangaluru coast on the southwest coast of India. This analysis provided valuable insights into the skills of the crew members operating the trawlers and also helped assess the stock status of commercially valuable fish species based on landings.

Profile and environmental impacts of Indian trawl fisheries

To comprehend the profile of the Indian trawl fishery and assess the environmental impact of trawling, an analysis of the catch/effort and emission status of the trawl fishery was conducted, utilising the base year 2017. Trawl fisheries data pertaining to fish landed in 2017 served as the basis for calculating the carbon emissions per kilogram of fish. The study employed a 'cradle to gate' approach[20,21], concluding with the distribution of fishes to households or processing plants. System input data, including craft and gear construction materials, fuel used for fishing, energy for on-

Table 1. Habitat-based classification of finfish and shellfish groups considered in the present study

Fish/shellfishes preferring pelagic habitat	Fish/shellfishes preferring column habitat
Rastrelliger kanagurta	Uroteuthis (photololigo) duvauceli
Mugil cephalus	*Sepia* spp.
Bregmaceros mcclellandi	*Octopus* spp.
Chirocentrus dorab	Sharks
Sardinella longiceps	Silverbellies
Sardinella spp.	*Lactarius lactarius*
Tenualosa ilisha	*Parastromateus niger*
Nematalosa sp.	*Pampus candidus*
Coilia dussumieri	*Pampus chinensis*
Setipinna spp.	*Sphyraena* spp.
Stolephorus spp.	
Thrissina spp.	**Fish/shellfishes preferring benthic habitat**
Thryssa spp.	Skates/guitarfish
Harpadon nehereus	Rays
Hemiramphus spp.	Eels
Exocoetus spp.	Catfishes
Polynemus spp.	*Saurida* spp.
Trichiurus lepturus	*Epinephelus* spp.
Megalaspis cordyla	*Lutjanus* spp.
Decapterus spp.	*Lethrinus* spp.
Aluterus monceros	*Nemipterus* spp.
Other carangids	Other perches
Other mackerels	*Upeneus* spp.
Scomberomorus commerson	*Johnius* spp./*Otolithus* spp.
Scomberomorus guttatus	*Psettodes erumei*
Scomberomorus lineolatus	*Bothus* spp.
Acanthocybium solandri	*Cynoglossus* spp.
Euthynnus affinis	Penaeid prawns
Auxis spp.	Lobsters
Katsuwonus pelamis	Crabs
Thunnus tonggol	Stomatopods
Other tunnies	Bivalves
Isthiophorus spp.	Gastropods
Non-penaeid shrimps	

board ice storage, and electricity for frozen processing of harvested fish, were converted into an environmental indicator, i.e., 'CO_2eq,' using standard conversion factors. This conversion followed the guidelines specified by the Department for Environment, Food and Rural Affairs (Defra) and the Department of Energy and Climate Change (DECC), UK[22], consistent with the Kyoto Protocol and the assessment report of the Intergovernmental Panel on Climate Change (IPCC).

Although detailed information on bottom and off-bottom trawling operations is unavailable for the entire coast, the composition of fish catches provides useful insights into the fishing methods employed. This interpretation was further validated by records maintained by fishers. Using findings from international studies[9,16], the present study compared the carbon footprint of trawl fishing along the south-west and north-west coasts of India by examining different fish groups, including bottom-dwelling species (such as finfish and shellfish), column species that move between the seabed and the surface, and surface-dwelling species inhabiting the upper water column.

Results and discussion

The evolution of Indian trawl operations

Focus shift from single-day operating units to multiday operations: A decade, 1990–2000, marked a highly dynamic period in the evolution of the trawl fishery. Substantial modifications were implemented in trawl design, particularly in the meshes of front panels and head rope length, consistently increasing in dimension. The decade witnessed a continuous rise in the number of trawls deployed[13]. Multi-day fishing expeditions emerged during this era, initially spanning 2 to 3 days and eventually extending to 5 days.

Catch and effort trends of the Indian trawl fishery

The CMFRI has been categorising trawl fishery data since 2006. Present decadal studies show that, by 2012, the number of units operating in single-day trawling was 62.5%, while multiday trawlers accounted for 37.5%. In 2022, the percentage of units operating in single-day trawling was 60.40%, and multiday trawlers were 39.60%. However, the fishing hours expended by single-day operating units and multiday units showed a substantial difference. In 2012, 20.22% of fishing hours were expended by single-day trawlers (SDT), and 79.80% by multiday trawlers (MDT). By 2022, the contribution of SDF and MDF hours was 16.56% and 83.44% respectively, indicating a shift in Indian trawl fishery from single-day trawling to multiday trawling in deeper waters.

In terms of catch, the percentage of catch by single-day trawlers in 2012 was 22.21%, while that caught by multiday trawlers was 77.79%. In 2022, the contributions were 23.05% and 76.95%, respectively, showing the profound dominance of multiday operating trawlers in the Indian trawl fishery.

A notable shift in catch preference from shrimp to fish, particularly perches, became evident in the 1990s. The proliferation of fish processing units, notably those specialising in surimi, during this timeframe contributed to the transition from shrimp trawling to fish trawling, especially along the northwest coast. Fishing endurance extended to more than a week, and by the year 2010, ribbonfishes, threadfin breams, and cephalopods became focal points for trawlers along the northwest coast of India. The heightened demand for cephalopods in the European market, coupled with the establishment of European Union (EU)-approved plants, bolstered the targeted harvest of cephalopods throughout the west coast of India.

Divergent gear designs tailored to perches, ribbonfishes, and cephalopods played a crucial role in maximising the catch of specific resources. The pursuit of economically preferred species led to the spatial expansion of trawl fisheries along the seasonal availability gradient. This spatial expansion extended laterally from trawling along the northwest coast of India to the continental shelf of the southwest coast and vice versa. The enhanced spatial reach was facilitated by on-deck facilities, increased endurance, and improved mobility, reflected in an increase in OAL to 56–58 ft and engine power exceeding 300 horsepower. The duration of fishing trips witnessed a substantial increase, with trips extending to 15–20 days.

Deciding on target species

The trawl, recognised for its non-selective nature, made species-specific targeting unthinkable during its inception. Initially introduced to exploit the abundant shrimp and demersal fish resources in the region, the trawl fishery landscape underwent significant changes over the years. With the establishment of export-oriented processing units, various resources with a robust export market, such as ribbonfishes, became highly sought after by trawl fishers.

From the year 2000 onwards, several processing units obtained EU approval, leading cephalopods (squid and cuttlefishes) to emerge as preferred species for boat operators in Gujarat. Ribbonfish and threadfin breams became common targets along the Indian coast, necessitating modifications in trawl designs for targeted fisheries. The primary bottom shrimp trawl gear diversified into five major types in the region: shrimp trawl, perch trawl (bottom trawls), cephalopod trawl (column trawl), and ribbonfish trawl (pelagic trawl). Within each trawl type, various design variants exist. As a general specification in all cases, the foot rope length is longer by 6–9 m (3–5 fathoms), mostly by 9 m. The towing speed varies from 2 to 6 knots, with 2–3 knots commonly used during shrimp trawling. For ribbonfish, demersal fish, and Acetes trawling, the speed is around 4 knots, while squid trawling involves towing speeds of up to 6 knots.

Changes in fish composition by bottom and off-bottom dependency

An analysis of trawl data provides evidence of the trawler's off-bottom operation over time. Figure 1 shows changes in species composition since 2000, with a notable increase in pelagic and column-dependent species, while demersal species catches remained relatively unchanged. While analysing the percentage composition trend, pelagic species showed a sharp rise, and an increasing trend was observed in column fishes. In contrast, the catch trend of demersal species was negative (Figure 2).

Changes in the composition of targeted resources

Regarding individual species/groups, a notable shift in the species/group composition of trawl catch has been observed since 2000. In 1992, penaeid shrimps constituted the major species at 14.3%, followed by croakers at 11.5%. By 2002, penaeid shrimps continued to dominate the catch

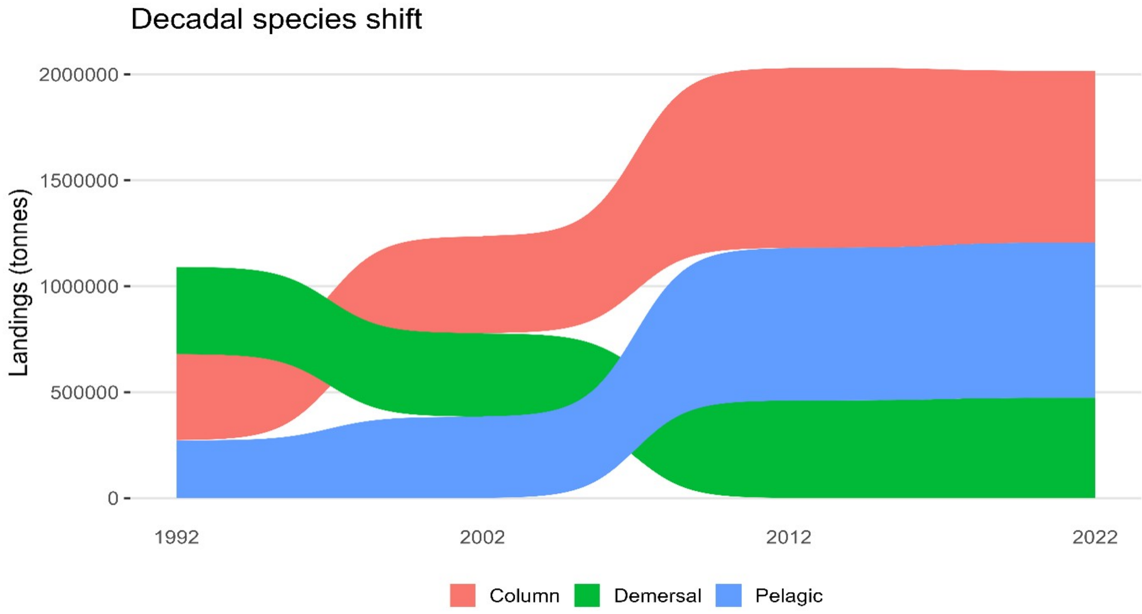

Figure 1. Trawl composition (%) indicating the increase in the pelagic column resources in the trawl fisheries of India.

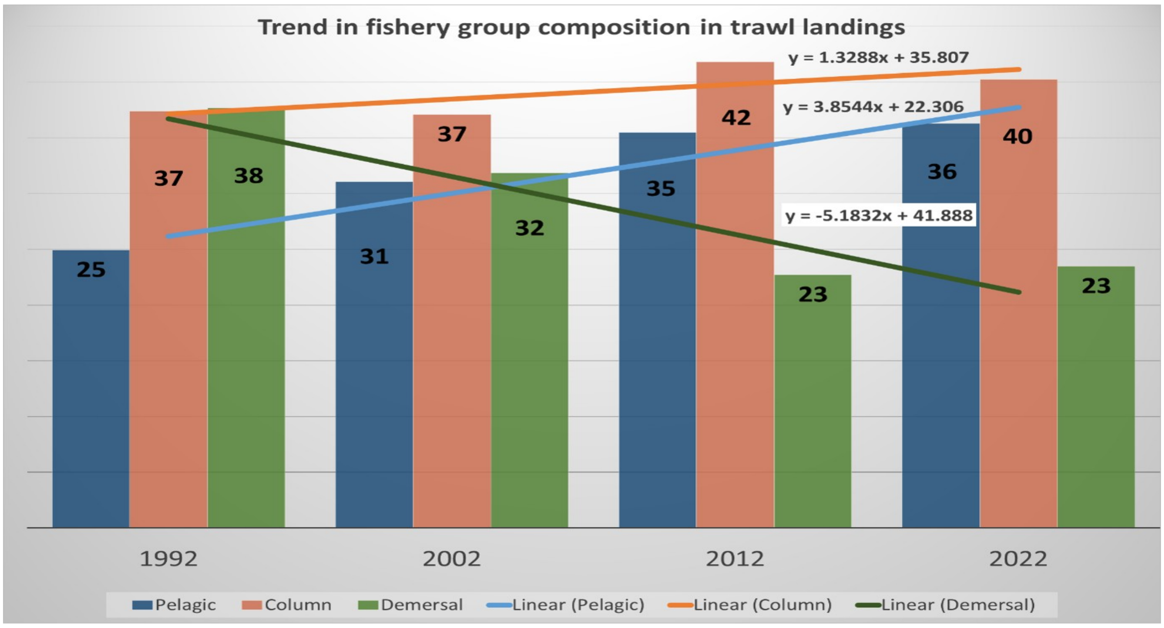

Figure 2. Trawl group composition indicating the trend of the pelagic, column, and demersal resources in the trawl fisheries of India.

at 13.7%, and from this point onwards, cephalopods, with an export demand in the market, contributed a higher percentage of representation at 8.0%.

As depicted in Figure 3, from 2000 onwards, column fishes such as threadfin breams (10.0%), cephalopods (8.7%), and pelagic fishes like ribbonfish (9.8%) contributed to the trawl catch along with penaeid shrimps (10.3%). The high demand for cephalopods in the European market, the high value of the single market for ribbonfish from China, and the demand for 'surimi' preparation from threadfin breams, especially for *Nemipterus randalli*, compelled fishermen to modify nets and fishing techniques to make trawling operations economically feasible, as discussed earlier. During this period, fishing voyages were extended to more than 10 days of operation.

Recent data analysis also indicates the pelagic and semi-pelagic operation of trawlers. The rise in Indian

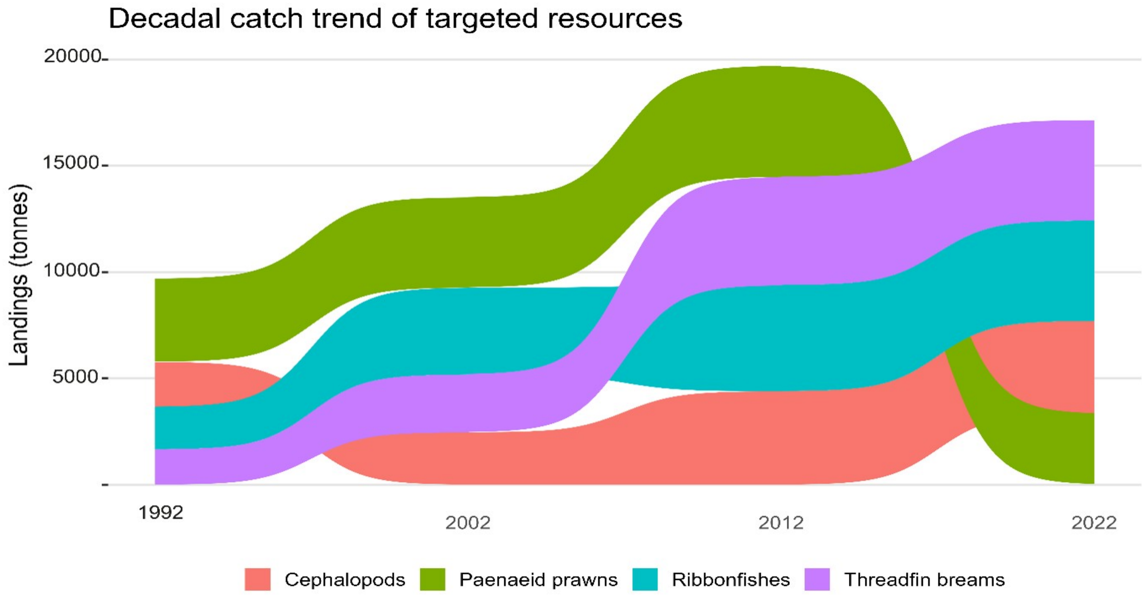

Figure 3. Decadal catch trend of targeted fishery resources in view of increased market demand.

mackerel landing (2.5%) serves as notable evidence of pelagic and semi-pelagic trawling operations during this period. In 2022, various species of column and pelagic preference dominated the fishery, with perched species, including threadfin breams, leading the trawl landing in quantity and percentage, exceeding 3 lakh t and contributing 15.2% to the total trawl fishery. Other dominant species in trawl landings included scads and other carangids (10.8%), ribbonfishes (9.2%), and cephalopods (8.7%). Penaeid shrimps constituted only 6.6%, and the entire demersal fish contribution was 23%. Indian mackerel landings showed a higher percentage contribution during 2022, with a 3.9% contribution, landing over 78,000 t.

Changes in species composition indicating reduced fishing pressure

Stomatopods, a highly ground-dependent species caught exclusively with bottom trawling activities, saw a reduction from 6.4% of trawl landing in 1992 to 3.6% in 2002, 1.30% in 2012, and the lowest at 0.50% in 2022. This reduction is mainly attributed to the decreasing dependence of trawlers on the bottom, a unique feature when discussing trawl fishery on a global scale. The landing-based indication of pelagic and semi-pelagic trawling is evident from the analysis provided in Figure 4.

Typically, once the multiday trawling and highly valuable export items are the main focus, earlier targets like single-day trawlers, like soles and stomatopods, are not the focus of targeted fisheries in most regions of the country. The alterations in their contribution to the trawl fishery can be regarded as indicative of the fishing pressure exerted across various strata of the fishery ecosystem. It is evident that the contribution of pelagic groups such as lesser sardines and anchovies is increasing, while the demersal group comprising soles and stomatopods (Figure 4) is not significantly subjected to fishing pressure.

Crustacean composition in trawl fisheries

Trawling was introduced in India to catch shrimp along the coast, mainly because of the high demand and export value in the market. This made the fishing method very popular among fishermen. Bottom trawling was the only method used until the 1990s. After new export opportunities opened up for cephalopods and finfish, there was a gradual and systematic shift in the target species. This shift was influenced by the high value and demand for cephalopods in Europe, ribbonfish in China, and threadfin bream for 'surimi' production in Japan and Southeast Asian countries. Technological improvements, such as high-speed engines and larger storage with better freezing facilities, made this transition faster. As a result, fishing gradually shifted from only bottom trawling to include mid-water trawling. This change is clearly seen in the percentage of shrimp in marine fish landings. Although the total production increased each decade, the share of shrimp decreased from 13.1% in 1992 to 5.7% in 2022 (Figure 5). Stock assessment studies on commercial crustacean species showed that the stock status of crustacean waters is healthy, and stock reduction cannot be treated as a reason for the reduction in percentage.

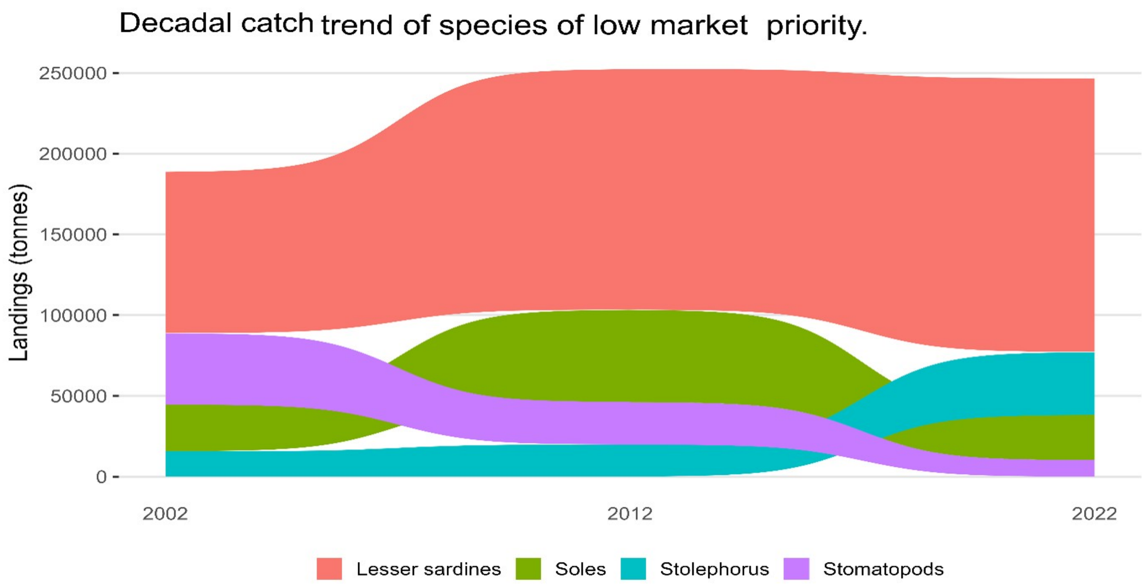

Figure 4. Comparative catch trend of traditional bottom trawl resources in comparison with pelagic resources.

The escalating composition of crustaceans in the global trawl fishery has been anticipated to raise ecological and environmental concerns[9]. To comprehend the Indian context regarding crustacean catch over the past four decades, a thorough analysis of catch trends was conducted. In the Indian scenario, the catch trend of crustacean resources exhibits a declining pattern, and as depicted in Figure 5, the reduction in percentage was also substantial. Boenish *et al.*[9] stated that globally, wild decapod crustacean fisheries are growing faster than fisheries of any other major group, contributing to 94% of the projected increase in global fishery carbon emissions due to low capture efficiency. However, the Indian scenario reveals a drastic reduction in the percentage of crustaceans in trawl landings. The prevalence of off-bottom trawl fisheries in Indian trawling was elucidated through participatory research with commercial trawlers, as well as an analysis of bottom and pelagic-dependent fish groups. Since 2000, the Indian trawl fishery has shown a sharp increase in pelagic fish and a reduction in demersal groups, while column-preferring groups have exhibited an increasing trend. Demand-driven modifications in trawl nets resulted in an increased targeting of pelagic column fishes, and the analysis of non-targeted resources indicated low pressure on benthic biotas.

Changes in the trawl sector in response to the changing demand

A study employing participatory research in commercial vessels, utilising specifically designed questionnaires, was employed to gather offshore data concerning fishing operations and target fisheries. The information derived from the participatory research programme conducted in 2018 along the northwest coast of India and the southwest coast of India sheds light on the evolutionary trends within the trawl fishery in India.

Indian trawl operators demonstrated ingenuity by adapting trawl designs to specifically target column and pelagic fishes, successfully mitigating pressure on the ocean bottom. This innovative strategy positions Indian trawling as an exemplar of best management practices, distinguishing it from the global scenario characterised by destructive trawling practices. The alteration of trawling nets was shifted to off-bottom trawling (primarily for cephalopods and ribbonfishes). Although these changes were initially driven by market demands, they ultimately led to the conservation of benthic biota.

The Institute of Fishery Technology, Kochi, which is the sole institute taking care of the design of craft and gear in the fisheries sector in India, observed that trawler fishermen in India cannot depend on shrimp and associated species alone for viable commercial operations any more, and there is a need to adopt responsible alternate trawl systems for harvesting large demersal and semi-pelagic species. The Central Institute of Fisheries Technology (CIFT), Kochi, developed the CIFT semi-pelagic trawl system as an alternative to shrimp trawling for the small-scale mechanised trawler sector following extensive field trials.

McConnaughey *et al.*[16] conducted a comprehensive review and assessment of the efficacy of management measures and industry initiatives aimed at mitigating the adverse impacts of trawling on seabed habitats and biota, encompassing alterations in gear design. As part of the

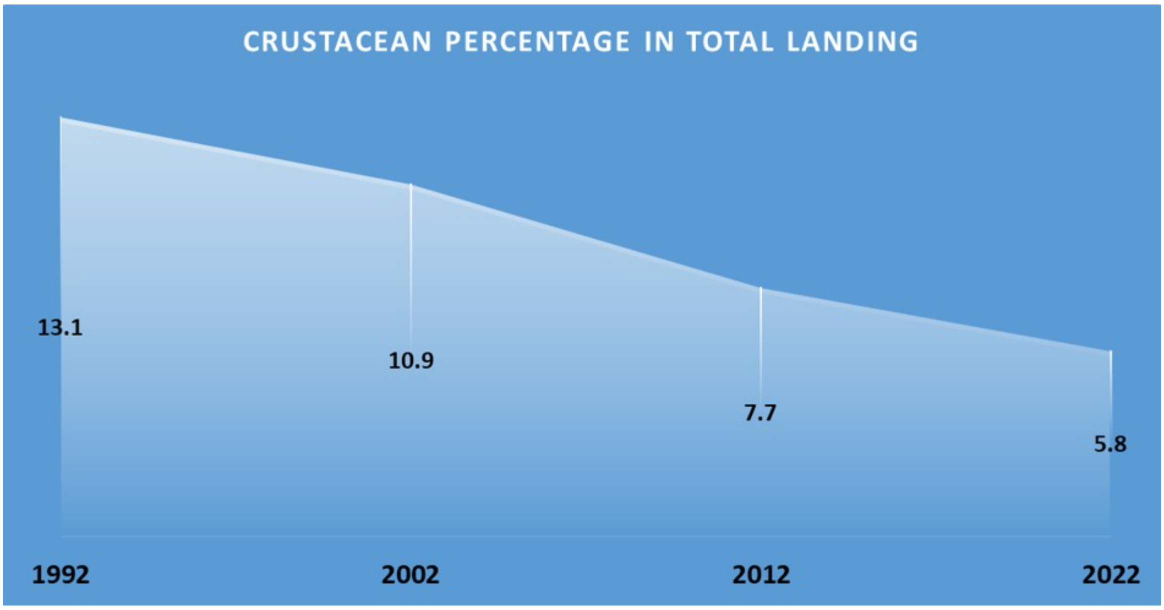

Figure 5. Progressive reduction in the percentage composition of crustacean contribution in the trawl landing.

evaluation of best practices implemented in this context, the operational aspects of the Indian trawl fishery were scrutinised utilising meticulously structured data collection schedules and participatory cruises conducted aboard selected commercial trawlers along the northwest and southwest coasts of India during 2018 and 2019.

Regional studies on trawl fishery changes

Apportioning of different nets in trawling operation

Trawlers often use different types of trawl nets, such as shrimp trawls, perch trawls, cephalopod trawls and hairtail trawls, depending on the fishing area. Along the Gujarat coast, trawlers spend about 40%–45% of their fishing days each season targeting largehead hairtail using mid-water trawl nets (based on personal communication with trawl skippers). To understand how trawling is done in the field, monthly data was collected on bottom and off-bottom trawl operations. The results showed that off-bottom trawling is more common than bottom trawling along the northwest coast of India in every month. On average, about 67% of the trawling off the Gujarat coast during the study period was off-bottom trawling.

Azeez *et al.*[23] also reported that trawlers from Veraval, Gujarat, regularly use different types of trawl nets, including shrimp, perch, cephalopod, and hairtail trawls, depending on the fishing grounds. These trawlers spend around 40%–45% of their fishing days each season targeting mid-water species in the area.

The participatory research programme was carried out in Veraval and Mangaluru during 2018 and 2019 to understand the field-level application of the trawlnets. It was found that generally the fishing operation extends for more than 10 days, and according to the species availability, the fishermen change the nets within a fishing trip.

The predominant usage of off-bottom nets is the major observation from the study from both case studies. Average bottom trawling was found to be reduced to 33% of the total operation in Veraval and 27% of the operation in Mangaluru (Figure 6). Semi-pelagic trawling focusing on cephalopods and ribbon fishes and threadfin breams was done as a target-orientated operation. Significantly, Indian trawl fisheries markedly differ from global industrial trawling, chiefly due to the absence of rigid operational plans for the vessels. Despite an enumerated trawler fleet strength of 30,772 (ref. 2), the vast majority of these vessels measure less than 20 m in OAL. Merely 63% of these trawlers are consistently operational, as their activity hinges exclusively on operational profitability. Typically organised in familial or partnership configurations, trawler operators often own multiple vessels. Initially, one trawler is dispatched for fishing as a pilot attempt to gauge resource feasibility at the season's outset. Successful pilot attempts prompt the entire group to deploy all trawlers based on the net requirements for the specific resource group.

Trawls with longer wings, designed to specifically target off-bottom resources in the Indian Exclusive Economic Zone (EEZ), were tested on the research vessel FORV Sagar Sampada[24]. The catch mainly included semi-pelagic species like *Tachysurus* sp., *Sphyraena* sp.,

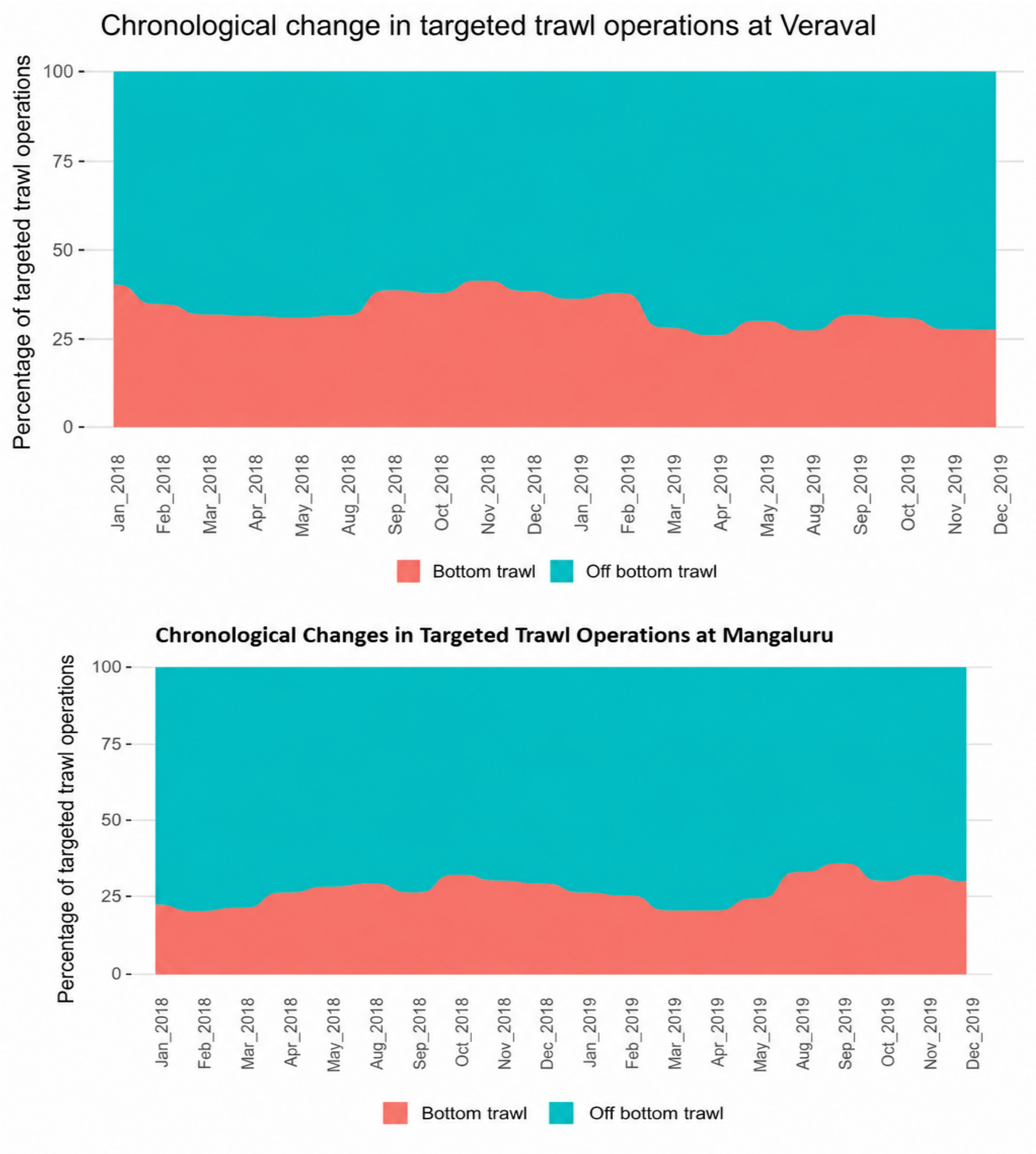

Figure 6. Effort allocation in the fishing grounds by trawlers operating from the northwest and southwest coasts of India, based on participatory research conducted during 2018–2019 at Veraval and Mangaluru.

Trichiurus sp., *Priacanthus* sp., *Megalaspis* sp, *Protonibea diacanthus*, *Nemipterus japonicus*, *Polynemus indicus*, *Saurida tumbil*, *Scomberomorus* sp., *Chirocentrus* sp., *Chorinemus tol, Pseudocaranx dentex*, squid, cuttlefish, and other off-bottom fish, which together made up more than 85% of the total catch. This confirmed that the trawl was effective in targeting semi-pelagic fish species[24].

McConnaughey *et al.*[16] reviewed and evaluated the effectiveness of management measures and industry actions aimed at minimising the impacts of trawling on seabed habitats and biota, including changes in gear design, spatial controls, impact quotas, and effort controls. In adopting best practices, Indian trawl operators modified trawl designs to target column and pelagic fishes, thereby reducing pressure on the ocean bottom. This innovation positions Indian trawling as a best management practice, distinguishing it from the global scenario of destructive trawling.

Discussions surrounding the prohibition of trawl fishery for environmental and benthic ecology conservation[14,15] and the series of findings highlighting environmental degradation due to bottom trawling[4,5,7,25–27] have placed global trawling practices in an uncomfortable position. Consideration is being given to assessing the ecological and environmental benefits of banning trawl fisheries. In this context, the Indian trawl fishery, which sustains the livelihoods of millions in India, underwent an in-depth analysis of fishery data and operational details. Contrary to global concerns, the Indian trawling industry exhibited a dependence on bottom-dwelling species for demand-driven reasons, as evidenced by recent catch compositions. The trawl fishery, contributing over 50% to marine fish catch, is highly aligned with best practices in trawling[16].

Semi-pelagic trawling is designed as a hybrid technique that can capture fish distributed on- and off-seabed[27]. Semi-pelagic trawling can be considered when doors are fished off-seabed and the trawl is on-seabed; trawl is off-seabed and the doors are on-seabed, or in a hybrid fishing situation where either doors or trawl are moved on- or off-seabed as fishing conditions or motivations change[27]. Semi-pelagic trawl gear does not come into contact with the seabed, resulting in less damage to the seabed. Using a semi-pelagic trawl instead of a demersal trawl may potentially reduce the impact on the seabed and disturbances or damages to benthic invertebrates[28].

Profile of Indian trawl fishery and environmental impact of trawling

Carbon footprint of Indian trawl fishery

In calculating the carbon footprint of trawl fisheries, diesel usage emerges as the major contributor to carbon emissions. From a carbon emission standpoint, the emissions intensity (kg CO_2eq/kg) is the indicator of carbon dioxide equivalent gas emission from fishing activities. The pre-harvest stage, which includes boat-making and net-making activities, emitted just over 0.04 million t of CO_2eq. Emissions. The actual fishing operation, encompassing activities from carrying to the sea during fishing, accounts for the highest emission at 3.07 million t of CO_2eq. The post-harvest stage, which includes transportation and ice requirements until reaching households or processing plants, contributes 0.60 million t of CO_2eq. In 2022, the carbon footprint per kilogram of fish, the emission intensity per kg of fish production in trawl fisheries, was 1.81.

Zonal analysis: Since fishery operations were extended horizontally and vertically, multi-day operating fishing vessels carried out fishing operations far and wide. Hence, each state's landing was not from the functional state alone; there was a need for zone-wise analysis of fishery data and emission characteristics. Spatial studies of Indian marine fisheries[29,30] also emphasised the need for zonal fishery regulation bodies to effectively implement the fishery regulations in India. In light of these recommendations, detailed zone-wise emission status was derived in the present study. For getting a zonal figure, follow the climate-based zonal classification[31]. Gujarat and Maharashtra were classified as northwest (NW); Goa, Karnataka and Kerala as southwest (SW); Tamil Nadu, Pondicherry and Andhra Pradesh as southwest (SW); and Odisha and West Bengal as northeast (NE). The region-wise, groupwise percentage of landing is given in Figure 7. The Indian trawl fishery, on the east coast of India, has significantly lower emission intensity (1.55 kg in the southeast and 1.62 kg southwest) compared to the west coast (1.73 kg in the northwest and 2.17 kg in the southwest). There was found to be a high positive correlation with benthic catch and a negative correlation with pelagic catch (Table 2).

The Indian trawl fishery has a much lower carbon emission rate (1.66 kg CO_2eq per kg of fish) compared to the global average of 2.2 kg CO_2eq per kg (ref. 32). The lower emissions along the northwest coast of India, where off-bottom trawling is common, suggest that reducing dependence on bottom trawling can benefit the environment and support ecological conservation.

Since most of India's wild-caught marine exports come from trawl fisheries[33], the lower carbon footprint gives Indian trawl fisheries an advantage in the export market. It may also help them qualify for carbon credits or trading programmes. Overall, this highlights Indian trawl fisheries as environmentally friendly and sustainable sources of livelihood.

According to studies from other regions, fisheries that target pelagic fish produce much lower carbon emissions—about 40 times less—than those targeting crustaceans. Similarly, fisheries targeting cephalopods and demersal fish emit only 24%–35% as much as crustacean fisheries[31].

While CO_2 emissions per kilogram of fish (CO_2eq/kg) can be used to measure the environmental impact of Indian marine products compared to those from other countries, there is an urgent need to improve fuel efficiency in the Indian trawl sector. Many studies have shown that Indian trawlers often exceed recommended engine power limits, which were set by CIFT to ensure fuel efficiency. Engine power is increasing compared to vessel size, mainly to enable high-speed trawling for pelagic fish.

While appreciating the low carbon emissions per kilogram of fish seen in India, it cannot be treated as fuel efficiency of fishing vessels, but mainly because of the high landings of pelagic fish by trawlers. This cannot be seen as a positive sign for long-term sustainability. To ensure sustainable fishing, trawlers should follow fuel-efficient

Table 2. Percentage composition of benthic, column and pelagic species and the carbon footprint of trawling in NW, SW, SE and NE zones of the Indian coast

	Carbon footprint (CO_2eq, emission, kg of fish)	Benthic %	Pelagic %	Column %
NW	1.73	45.69	39.25	15.06
SW	2.17	47.78	37.27	14.95
SE	1.55	30.57	50.35	19.08
NE	1.62	27.98	53.49	18.53
Correlation coefficient	-0.789860762	C02eq, emission to Pelagic percentage		

NW, Northwest; SW, Southwest; SE, Southeast; and NE, Northeast.

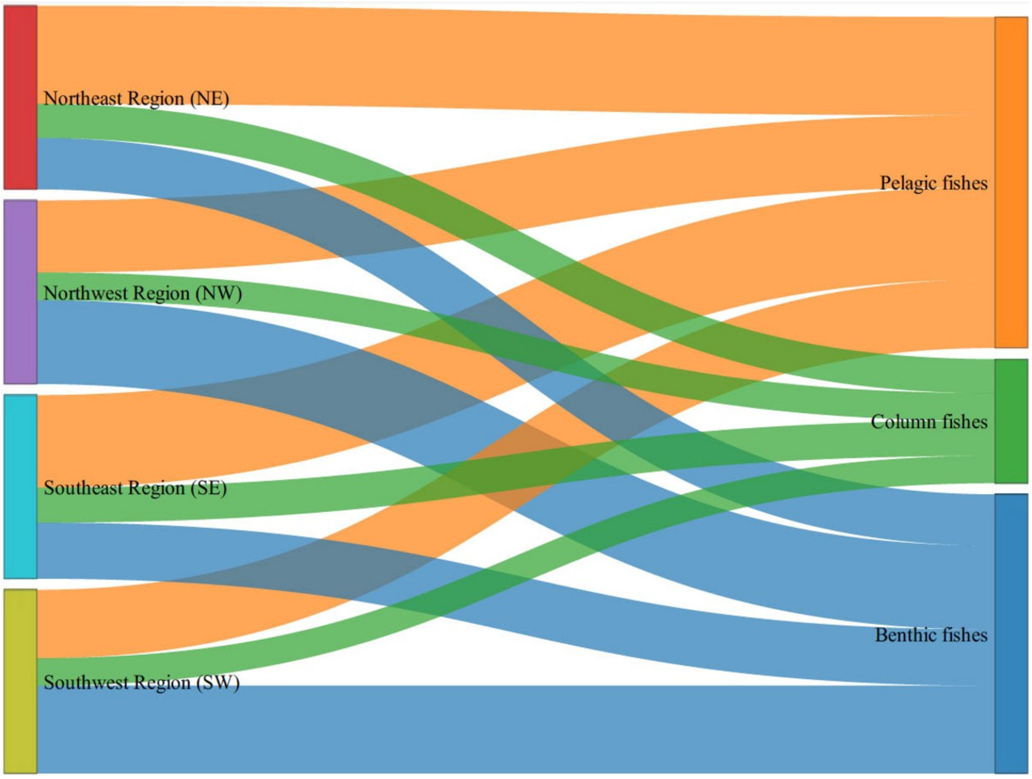

Figure 7. Representation of pelagic, column and benthic fishes across different zones of the Indian coast during 2022.

practices and adhere to the recommended engine power-to-vessel size ratios set by fisheries research institutions.

Optimisation of trawling speed for environmental and ecological sustainability

According to Baiju and Boopendranath[34], trawlers with an OAL of 10–20 m achieve optimal fuel efficiency when powered by engines rated at 220–250 horsepower (hp). Based on this, strict guidelines were issued to various states. These recommendations were mainly for bottom (benthic) trawling. However, some maritime state governments included adjustments in their Marine Fisheries Regulation Acts (MFRA) to meet the speed requirements of semi-pelagic trawling.

Considering the speed needed for semi-pelagic trawling beyond territorial waters, engine power above 250 hp was allowed in certain cases along the southwest coast of India[29]. However, engines with power above 350 hp are mostly used for pelagic trawling, which helps trawlers chase fast-moving pelagic fish shoals. This practice has been found to be highly damaging to long-term fishery sustainability. In 2014, the CIFT designed an 18 m steel trawler that consumed an average of 13–14 L of fuel per hour, based on 15 h of daily fishing[35]. This was considered fuel-efficient at the time. However, a study in 2020 across different maritime states showed that modern multi-day trawlers consume between 26.7 and 32.3 L of diesel per hour (average 30.1 L), and deep-sea trawlers consume between 43.86 and 52.8 L per hour (average 48.5 L)[36]. Marine diesel engines from 13 different manufacturers were in use.

Until 2000, almost all trawlers operating in Kerala had engines under 150 hp. By 2012, more than 70% of them had engines above 150 hp, with some even reaching 450–500 hp. This rapid increase in engine power, especially in trawlers over 18 m in length, highlights the urgent need to regulate vessel engine capacities to conserve fuel and reduce GHG emissions[37]. A study on fuel efficiency and GHG emissions of trawlers along the southeast coast of India[38] found a significant increase in fuel use. This was mainly due to unscientific modifications to trawlers, which increased drag and resistance in the water. As a result, a 20 m trawler was estimated to use 204.82 L of extra fuel per trip. The study also noted that current CO_2 emissions from trawlers in this region could be reduced by 43.4% by improving trawl design and lowering trawling speeds. Economic analysis[39] showed that the cost of operating a trawler for pelagic fishing on a 10-day trip is around $6,605, with a major portion spent on fuel. This highlights the need for fishermen to reconsider using high-powered engines just to compete.

Globally, falling catch rates have led to intense competition among trawlers. In response, many fishermen have installed larger engines to stay competitive, often unnecessarily. In India, low catch rates of key commercial species have also driven the trend of using oversized engines, leading to overcapitalisation in the fishing industry. In this situation, reducing fleet size is urgently needed. Rijnsdorp *et al.*[40] studied the Dutch beam trawl fleet and found that increased engine power and competition among vessels affected how fishing effort was distributed. They stressed the need for more studies on fleet competition and the development of management models to help control fishing effort effectively.

Technology-driven advantages to the trawlers and its impact of Indian fishery

While off-bottom trawling is known for causing less damage to the sea floor, its benefits are being reduced in some parts of the country due to the growing use of high-speed engines, advanced fish-finding technologies, and quick access to forecasted fishing zones provided by government agencies. In these areas, trawl operators are investing heavily in such technologies, which reduces the environmental advantages of off-bottom trawling.

In Turkey, there is a legal rule that allows a one-time switch from bottom trawling to pelagic trawling during the fishing season. Due to high catch volumes and increased profits from pelagic trawling, more vessels have started using this method in recent years[41]. However, the increased catch of oil sardines, other sardines, Hilsa shad, other shads, *Coilia*, *Setipinna* species, *Stolephorus*, *Thryssa*, Bombay duck, *Acetes* species, and similar fish suggests the growing use of pelagic trawlers with high-speed engines. Experimental studies in Veraval and Mangaluru showed that pelagic trawling is often being carried out under the name of off-bottom trawling. In 2018–2019, pelagic trawlers made up 40% and 34% of operations at these two landing centres, respectively. In India, optimising engine speed is urgently needed to ensure the sustainability of pelagic fish resources.

Vivekanandan[31] observed that high-speed trawling using powerful engines (around 400 hp) has been introduced in traditional trawlers along the southwest coast of India. These trawlers mainly target bulk fish in subsurface waters, and most of the catch consists of juveniles of commercially important species. Studies on the east coast of India have also shown that the recent trend of high-speed trawling has increased the number of juvenile fish in the catch, especially among pelagic species. Behera *et al.*[42] reported that catches from multi-day trawlers operating along the northeast coast included juveniles from 20 commercial species, making up about 55.3% of the total catch. Similar findings were also reported along the southwest coast[43,44].

Dineshbabu *et al.*[45] reported that multi-day trawlers operating off the southwest coast of India between 2007 and 2009 covered a fishing area of about 40,666 sq. km. However, some parts of this area were avoided because they were not suitable for bottom trawling. As a result, only about 75% of the area (around 30,221 sq. km) was actually trawled. The remaining areas were later explored and found to be unsuitable for trawling due to rocky patches. A comparison with data from 2012 to 2014 showed that the fishing area had expanded within the same zone, with around 90% of it now being used—mainly for pelagic and high-speed off-bottom trawling. The researchers warned that this expansion into previously untouched and naturally protected marine zones could harm sensitive ecosystems, which are important for the long-term health of marine life in Indian waters. They recommended strict enforcement of rules for off-bottom trawling, including the use of approved engine and vessel combinations and proper mesh sizes, to improve fishing practices before serious damage occurs.

A study on European Marine Protected Areas (MPAs) by Dureuil *et al.*[46] found that high-speed trawling within protected zones reduces the effectiveness of conservation efforts in global fishing hotspots. The study highlighted that pelagic speed trawling above sensitive MPAs is one of the most harmful human activities in these areas.

State governments have different legal tools to stop unsustainable fishing practices. Most maritime states have rules called MLS to protect young fish. However, enforcing these rules strictly is expensive, which makes them less effective.

From a responsible fishing point of view, fish meal and fish oil factories choose not to accept fish caught below the MLS size. If these rules are properly enforced, this approach can better control the harm caused by illegal fishing.

Conclusion

In conclusion, the introduction of semi-pelagic trawling in Indian trawl fisheries has helped reduce reliance on bottom trawling and significantly lowered seabed damage. The carbon footprint of Indian trawl fisheries is also environmentally friendly, with emissions of 1.66 kg CO_2eq/kg, which is much lower than the global average of 2.20 kg CO_2eq/kg for marine exports. However, there is an urgent need to reduce engine power according to vessel size to improve fuel efficiency and limit high-speed pelagic trawling. It is also important to determine an optimal fleet size based on available resources, as declining catch rates have increased competition among fishers, leading to unscientific changes in vessels and gear. Recent catches from high-speed pelagic trawling contain many juvenile fish, which are mostly used in reduction industries. To protect fish stocks and sustain the benefits of semipelagic trawling, reduction industries should voluntarily reject fish below the minimum legal size, and fisheries officials must strictly monitor the purchase of such fish.

Disclaimer: The results reported in the present study are solely the findings of scientists who have worked on various projects related to the development and management of trawl fisheries in India.

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