Understanding recent variations in the zero year-class entries of Indian oil sardine and its impact on the fisheries of Kerala

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The Indian oil sardine (IOS) fishery along the Kerala coast from 2021 to 2024 was assessed using an eco-region approach, revealing a significant increase in recruitment in 2024 compared to previous years, and at varying scales. The ecosystem productivity indicators showed a stronger influence on recruitment dynamics than the biological indicator of spawning stock biomass. The relative contributions of micro-, pico-, and nano-plankton functional groups indicated linkages with the physio-biological dynamics of IOS and need further research. The present study highlights region-specific environment variability, especially during the pre-spawning and pre-recruitment periods, that needs to be adequately integrated into stock assessments and dynamic management frameworks. Development of species-specific, eco-physiological indicators for timely fisheries governance interventions to sustain the fishery of IOS under changing oceanographic conditions and supporting the development of short-term forecast models is recommended.

Keywords: Eco-regions, primary productivity, sardine, small pelagic, spawning stock biomass.

THE Indian oil sardine (IOS) *Sardinella longiceps* is a major single-species fishery in India, driving the trend of the national marine fish landings every year. It is mostly present in Kerala on the southwest coast of India, although climate and market-induced factors have contributed to its fisheries developing on the eastern coast states such as Tamil Nadu, as well as to the more northern states such as Maharashtra, in recent years. The year 2024 saw an exceptional number of oil sardine recruits (around 10 cm in size) entering the fishery along the Kerala coast. The trend was pronounced in the northern districts, especially Kozhikode, and gradually declining as it moved south, from Ernakulam to Thiruvananthapuram district. At the same time, the fishers expressed concern that the sardines were apparently 'not growing' and only juvenile size groups (10–14 cm total length) were appearing in the fishing nets deployed. In the short-lived species, recruits (0 year-class) are a significant component of the annual biomass, and recruitment variation is a critical factor in stock assessments[1]. The number of IOS recruits in the northern Kerala coast was exceptionally higher in 2024 than in all the previous years since 2021 and to a lesser extent in the southern locations. The reported ability of the El Nino Southern Oscillation (ENSO) to influence the IOS fishery, along the Kerala coast by affecting its behaviour and biology [2,3] led to the question of what factors favoured the exceptional recruitment success of the IOS in 2024 after a gap of around twelve years. Studies explaining the high variability of the oil sardine fisheries in India have concluded that multiple environmental factors affect this short-lived small pelagic fish with a high population turnover rate[4–7], making accurate forecasts difficult. Recruitment is a major cause of variations in fish population sizes, and identifying the fine-scale processes in the recruitment pathway can significantly improve fisheries management advisories[8]. In experimental conditions, prey availability and quality limit sardine growth[9] while complex biogeochemical and ecological factors at spatio-temporal levels in the Arabian Sea affect its fisheries[10,11]. Since recruitment and growth processes significantly influence fish population dynamics, this study has used an eco-regional approach to understand the recent surge in recruitment in the IOS fishery along the Kerala coast and identify biology-based indicators for use in stock assessments and management advisories.

The length frequency and biology data of the IOS from 3 eco-regions (Vizhinjam 8.3932°N, 77.0046°E; Kochi 9.9312°N, 76.2673°E and Kozhikode 11.2588°N, 75.7804°E) of Kerala coast in the south-eastern (SE) Arabian Sea were used in the study. Cohort analysis for population status and recruitment trends was done in Tropfish R[12]. Annual mean condition factor (MCF) at each locality using respective length–weight relationships as $K_{mean} = 100\,aL^{b-3}$ was assessed[13]. Here, a and b are the parameters estimated from the Length (L) and Weight (W) relationship $W = aL^b$ of the fishes sampled annually from each eco-region. The variables of environment (sea surface temperature (SST), marine heat waves (MHWs), rainfall, monthly chlorophyll, and phytoplankton size classes (PSC)) were assessed. The SST data (OISST Version 2.1) of spatial resolution 0.25 degrees and daily temporal resolution[14] archived by the NOAA National Centers for Environmental Information, USA, was used for the estimation of MHW[15]. The monthly chlorophyll-a (chl-a) concentration datasets, with a spatial resolution of 4 km were downloaded from the Ocean-Colour Climate Change Initiative (OC–CCI version 6) project (http://www.oceancolour.org) archive with the

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Table 1. Indicators used in the present study

Indicator	Rationale
Spawning stock biomass (SSB)	Potential egg production
Mean condition factor (MCF)	Impacts fecundity and larval survival rates through 'maternal effects' of egg quantity and quality
Recruitment numbers (Absolute)	Spawning success and larval survival
Recruit per spawning stock biomass (R/SSB)	Larval survival rates indicator
Plankton quantity and quality (C_m, C_p, C_n) – absolute and ratios	Early life stage prey quantity and quality that determines larval survival and recruitment
Sea surface temperature (SST) and Marine heat wave (MHW) occurrences	Overall habitat suitability

SeaDAS software for data processing. The individual PSC were assessed with an abundance-based model that assumes the total chl-a concentration is the sum of the individual PSC from pico (C_p), nano (C_n), and micro (C_m) phytoplanktons[16].

The recruitment process proceeds from pre-spawning stage factors (maternal condition, fecundity) to spawning (regressed spawning, atresia) and post-spawning larval survival (involves current and wind patterns influencing the egg and larval distribution, water productivity and food aggregations/patches, and larval feed match-mismatch) phases to their entry into the fishing grounds as recruits and becoming susceptible to fishing mortality[2,17] were used to base the indicators (Table 1). The widespread incidence of MHW in the Northern Indian Ocean was also reflected in the coastal waters of Kerala, during the period November 2023 to May 2024. Among the three eco-regions, the Kochi region experienced the longest episodes. This being the normal gonad maturation period preceding spawning in June–July, probably resulted in a very low sardine spawning stock biomass (SSB) level in 2024 (Table 2, Figure 1).

However, the recruitment trends in all the centres during 2024 were higher compared to earlier years, either in absolute terms (recruitment) or relative (Recruits/SSB or R/SSB) terms, indicating a favourable post-spawning and pre-recruit phase, in all the stations (Figure 1). Even at a very low SSB of $<$10%, recruitment in 2024 indicated higher larval survival rates in Kochi. The record number of recruits and the comparatively high SSB in Vizhinjam in 2022 were in sharp contrast to 2024, with a considerable reduction of SSB to 23%, and yet the R/SSB was high. Also, continuous recruitment was observed in the northern district of Kozhikode in 2024 as compared to the other regions (Figure 2). The 'recruitment states' hypothesis proposed recruitment independent of SSB and concluded that periods of environmentally induced low recruitment occur in marine fishes, which are unavoidable[18]. Other studies have also indicated a lack of any positive relationship between SSB and recruitment or being affected by environment and physico-biological factors other than SSB for a significant number of fish stocks[18–20], but it still rightly remains as a valuable precautionary reference point in fish stock assessments[21]. The IOS fisheries management that currently incorporates provision for preventing growth overfishing and ensuring adequate spawning stock by enforcing a minimum legal size[22] is therefore apt for ensuring suitable protection against any risks of overfishing, environmental uncertainties, and even any errors made in assessing the stocks. Rainfall trends at the three locations indicated that the variability was highest in Kozhikode in 2024, as compared to the other two eco-regions. The Spearman correlation analysis revealed strong and statistically significant positive relationships between rainfall and chlorophyll-related variables (C_m, C_p and C_n), indicating that higher chlorophyll concentrations are associated with increased rainfall (Figure 3). The SST showed significant negative correlations with the same chlorophyll variables, indicating its suppressive effect on chlorophyll levels. The IOS is a planktivorous fish with a diet dominated by diatoms[23–25]. In the Arabian Sea, diatom production peaks are associated with the North East Monsoon and South West Monsoon when nutrients are brought up by monsoon-related upwelling and other oceanographic processes[10]. Diatoms show substantial reduction of 50–60% during ENSO events[26], and significant inter-annual variations in the particle size composition are also reported[27]. The spawning peaks of several fishes, including the IOS, are aligned to these monsoons[28] due to favourable feeding regimes for the emerging larvae. The larval food quality determines the fish larval survival rates, and the plankton size should be big enough to be visible and smaller than its mouth opening diameter to be ingestible to the young

Table 2. Longest MHW incidences in the three eco-regions of Kerala coast during 2023–2024

Eco-region	MHW duration (Number of days)	MHW period	Mean intensity (°C)
Vizhinjam	71	05-12-2023 to 13-02-2024	1.0
Kochi	193	09-11-2023 to 19-05-2024	1.1
Kozhikode	125	15-11-2023 to 18-03-2024	1.1

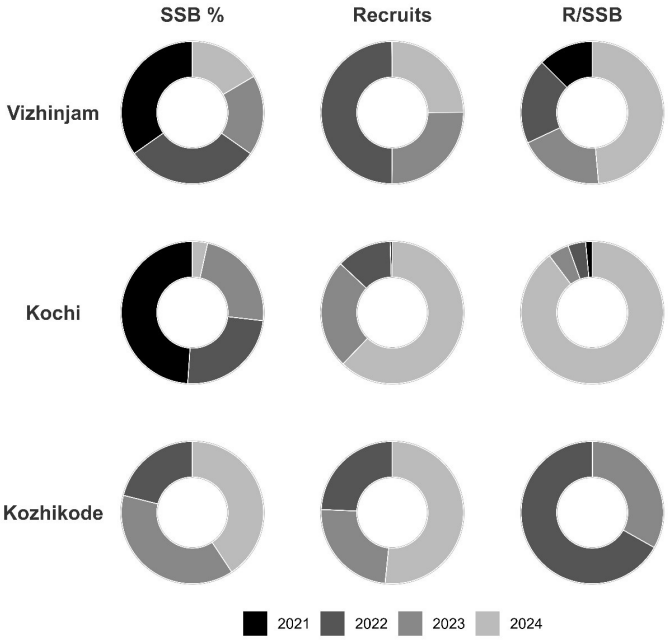

Figure 1. Indicators of recruitment dynamics of Indian oil sardine in the three eco-regions of Kerala coast. SSB, Spawning stock biomass; R/SSB, Recruit per spawning stock biomass.

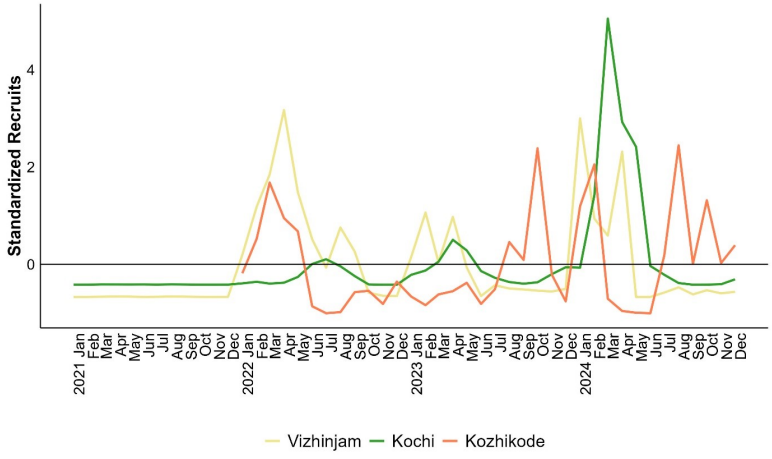

Figure 2. Recruitment trends in the three eco-regions of Kerala coast.

fish[29,30]. The post-larval stage measuring 7.64 mm with well-developed mouth and eyes reached within 30 days of spawning[31], is a critical phase, coinciding with its first feeding. Assuming that the environment was conducive for

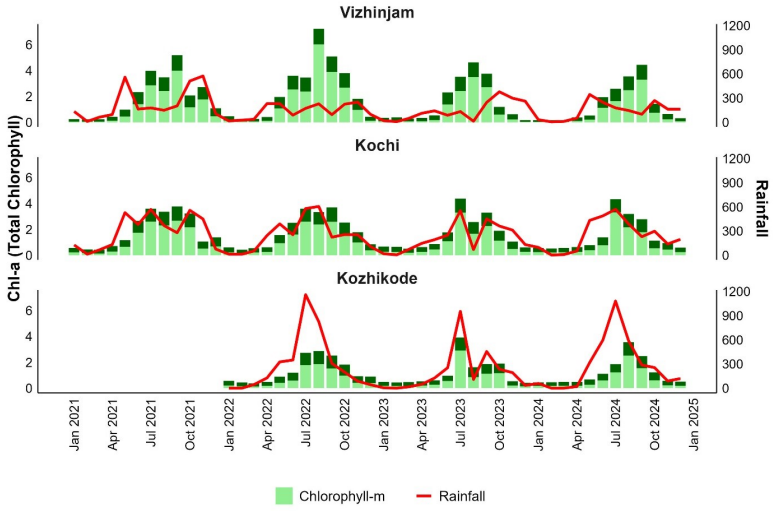

Figure 3. Rainfall and productivity trends in different eco-regions of Kerala coast (2021–2024).

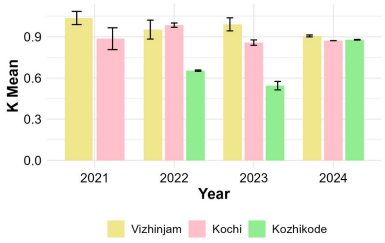

Figure 4. Variations in the annual mean condition factor in the three eco-regions of Kerala coast.

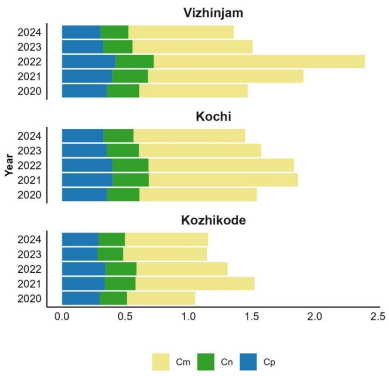

Figure 5. Eco-regional productivity patterns based on phytoplankton size classes.

such a rapid increase of recruits in 2024 through enhanced larval survival and growth, it is evident that the food availability and quality were critical positive factors for the IOS.

The impressive recruitment success of the IOS in 2024 was supported by rainfall trends in unison with the normal monsoon-related, upwelling of nutrient-rich waters that favour the dominance of microplankton (C_m) in comparison to pico (C_p) and nano (C_n) planktons which increases the efficiency of marine food chains[27,32]. At Kozhikode, the year 2024 showed a record recruitment, indicating a sustained level of high C_m during June to October with a peak in August. The MCF of the IOS was highest in 2021, when the peak of $\sim$2.5 mg/m^3 of C_m continued for an extended period through July, August, and September at Kochi as compared to other years. The C_m content indicated a drastic decline after the month of October over the years in all the regions (Figure 3). The declining trend of C_m over the annual cycle in 2024 was most pronounced in Kozhikode and may be attributed to its feeding strategy, which favours microplankton as optimal feed[24,25]. The phytoplankton abundance, species composition, and cell size are affected more by grazer interactions than even nutrient status[33]. Increased grazing by a higher number of recruits, therefore, may be a reason for monthly phytoplankton fluctuations noted in this study. In the absence of juvenile fish and plankton surveys in the feeding grounds, this hypothesis needs to be looked at in more detail. Land runoff contributes to enhanced plankton biomass in coastal waters[34], although increased freshwater influx reportedly favours relatively smaller phytoplankton in comparison to larger phytoplankton[11,35]. During June–December 2024, the rainfall was 69% higher than normal only in Kozhikode district (https://wris.kerala.gov.in/mis/wd/home/rainfall-), indicating such changes in the coastal plankton community are plausible and possible impacts of such natural events on the IOS need to be evaluated holistically. Threshold

levels for larval anchovy survival were defined based on cell counts and cell diameter of feed particles in their feeding grounds[30]. *In situ* data on food availability and quality and larval densities for the IOS are currently not available, indicating a research gap to be addressed in IOS fish population dynamics models. Their feeding behaviour shifts from filter feeding (<0.1mm particles) to particulate (>1.2 mm) depending on the food available, which has associated costs in the feeding time and the energy required[36]. Feeding experiments on sardine have indicated that small pellets have to be eaten twice as much to attain the same growth and body condition, while the quantity of the large pellets in the diet affected its capacity to store reserve lipids[9]. In Vizhinjam, the year 2022 exhibited exceptionally elevated values of C_m – May (1.07), June (2.54), and a pronounced spike in August (6.02) coinciding with a high MCF (Figure 4), SSB, and the highest absolute recruitment numbers. The lipid cycles in IOS affected by food availability and its likely influence on reproduction and growth dynamics[37] are therefore relevant in the current context of recruitment variations. A general lower plankton productivity during October to March resulting in lower growth rates, is reported in earlier studies[38–40]. The additional stress of an exceptionally large recruitment during the fishing season of 2024, leading to competition for food, besides the quality of the plankton itself, resulting in lower growth and a temporary stagnation of size groups available to fishers, is therefore plausible. The stomachs of IOS analysed during the last quarter of 2024 and early 2025 were empty or in a poorly fed category, supporting this conclusion. Since 2021, the market prices for IOS have been high due to its lower availability in the fish landings, until the fishing season of 2024 started in August. As juvenile sardines appeared in plenty with the progress of the fishing season, prices drastically reduced to one-tenth. The new recruits constantly appearing were lean (60–70 count), affecting their consumer acceptance and leading the fishers to stop fishing these juvenile sardines. There are similar reports of fisheries for sardines becoming unattractive in spite of their high population abundance, caused by severe decrease in body size and condition due to environment-driven disturbances in the Gulf of Lions in the Mediterranean Sea[41]. This study unequivocally indicated that local primary productivity regimes influence recruitment dynamics of the IOS (Figure 5), creating localised impacts on the fishery. Another study confirms the suggestion that unusually strong year-classes or recruits increase competition for food resources, which can cause a decline in subsequent fisheries yields[42]. Some culling of the overabundant year-class through a regulated fishing mechanism is therefore desirable to prevent any unfavourable impacts on fishermen and consumers. In the present study, environmental factors both at the pre-spawning (mean condition factor) and the post-spawning phases (larval survival and recruitment) were critical for the IOS fishery in the SE Arabian Sea. A bottom-up, environment-driven primary productivity control on its population dynamics means management interventions needed are species-specific and dynamic enough for implementation in short time windows by regulating catch and fishing efforts. It also indicates that species-specific physio-biology and ecology-based parameters and indicators need to be more widely adopted in fish stock assessments, developing short-term fishery forecast models and fishery managers, while basing the decisions on fish harvest controls.

Conflict of interest. The authors declare no potential conflict of interest.

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