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Article

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Posted Date: September 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10366280/v1>

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Additional Declarations: No competing interests reported.

A modelling approach to identify habitat suitability for Indian squid (*Uroteuthis (Photololigo) duvaucelii*) in the northeastern Arabian Sea

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Abstract

The spatiotemporal distribution and habitat suitability of the Indian squid *Uroteuthis (Photololigo) duvaucelii* (D'Orbigny, 1835) along the northeastern Arabian Sea (off the coast of Maharashtra State) was investigated. Seasonal shifts in Indian squid abundance revealed three distinct trawl fishing patterns, with post-monsoon fishing in August concentrated between 17°N and 16°N at 20–40 m depth, moving southward in September to 16°N–15°N at 40–60 m depth with higher catch rates, and subsequently becoming more dispersed and extending northward to 17°N–20°N as the season progressed. The factors influencing suitable habitats of Indian squid were assessed using a generalized additive model (GAM). The model results indicates higher probabilities of occurrence of Indian squid to areas of SSHa (Sea Surface Height anomaly) of ± 0.2 to 0.4 m, salinity range between 34.5 to 35 psu, PAR (Photosynthetically Active Radiation) > 40 Einstein $\text{m}^{-2}\text{day}^{-1}$, combined with a SST (Sea Surface Temperature) in range of 27.5 to 29.5°C , a current speed of >0.3 m s^{-1} and Chl-a values > 2 mg m^{-3} . The model successfully predicts the known areas of high abundance of Indian squid in the northeastern Arabian Sea. Such habitat suitability studies are important for assessing the distribution and abundance of fish resources on a synoptic scale for sustainable fisheries management.

Keywords: Arabian Sea, Indian Squid Fishery, Monsoon, Habitat Suitability

Introduction

The distribution and abundance of commercial cephalopod stocks around the world showed wide annual fluctuations. In India, cephalopods are found to be of increasing importance in the marine fishery and many species are targeted for commercial exploitation. Although cephalopods contribute to 4-6% of the total marine fish landings in India (CMFRI, 2019), they are under heavy exploitation due to their high value and cent-per-cent export potential (Mohamed, 2012). This is reflected in the wide fluctuations in cephalopods landing in the recent past. This may be attributed to species' short life cycles, non-overlapping generations and subsequent lack of buffering of the stock from the effect of varying surrounding environmental conditions on spawning and recruitment success (Boletzky 1986; Boyle 1990; Rodhouse 2001; Piatkowski et al. 2001; Rocha et al. 2001; Guerra 2004; Boyle and Rodhouse 2005; Yu et al. 2016; Sajikumar et al. 2018; Yu et al. 2019; Zhou et al. 2019). Squids are short-

lived, fast-growing highly sensitive to changes in surrounding environmental conditions (Coelho 1985) and their distribution is rather scattered which prevents large-scale exploitation. Many collapses in squid fisheries across the globe (*Todarodes sagittatus* in the northeast Atlantic or *Illex illecebrosus* in the northwest Atlantic) are left unexplained about what had been the main reason for such a collapse - negative environmental conditions or fishery or probably both. The Indian squid fisheries off Maharashtra, India like elsewhere in the world, is influenced by oceanographic factors. During the southwest monsoon, the strong south equatorial current i.e. Somali current which originates from Africa forms part of the anticyclonic circulation and touches the north-eastern Arabian sea off the Maharashtra coast. During the northeast monsoon, offshore winds induce primary production along the coast (Solanki et al. 2015). Fish populations should not be considered independently of their environment (Sharp 1997; Parsons and Harrison 2000) and protecting their habitat is critical for ecosystem-based fisheries management.

Based on their documented association with environmental variables, habitat suitability modelling (also known as species distribution modelling) is a technique for forecasting whether a place would be suitable for a species or group of species. Different techniques available to model habitat suitability (i.e. generalized linear models, generalized additive models, classification regression trees, maximum entropy approaches, artificial neural network, ecological niche factor analysis, multivariate adaptive regression splines, etc.) have been reviewed by Guisan and Zimmermann (2000). Among them, the Generalized additive model (GAM) which is an extension of the general linear model (GLM) allows the inclusion of both parametric and non-parametric effects of an environmental (explanatory) variable on fish abundance (response variable) (Wood 2006; Wood and Augustin 2002). GAMs initiated a real advance in the understanding of the abundance variability of fish resources in relation to their surrounding environment. An understanding of the interrelation between environmental parameters and squid abundance may reduce bias in the survey and predict the response of a population to environmental changes (Mohamed et al. 2018).

Material and Methods

Study area

The Maharashtra state has a coastline bordering the northeast Arabian Sea of about 720 km stretched across six maritime districts namely Palghar, Thane, Mumbai, Raigad, Ratnagiri and Sindhudurg with a continental shelf area of 112 thousand km². The study area was from 15.7°N to 20.1°N to 70°E to 73.5°E in the northeastern part of the Arabian sea (Fig 1).

The marine fisheries of Maharashtra like elsewhere in the world are influenced by oceanographic factors. During the southwest monsoon, the strong south equatorial current i.e. Somali current which originates from Africa forms part of the anticyclonic circulation and grazes the northeastern Arabian sea. During the northeast monsoon, offshore winds induce primary production along the coast.

On-board fishing data

The marine fisheries of the state are multispecies with relatively fast-growing and continuously breeding fishes. In late 1960, with rapid mechanization in the fisheries sector, trawling emerged as the dominant fishing practice in the state. Along the Maharashtra coast, trawling targets

shrimps, cephalopods and demersal finfishes. In the recent past, species-specific trawl designs were developed. The squid fishery geospatial data (Fig. 1) were collected from 2017 to 2019 from multi-day trawlers operating at New Ferry Wharf, Sassoon Dock, Versova fish landing centre of the Mumbai district and Harne and Mirkarwada fish landing centre of the Ratnagiri district of Maharashtra covering the entire coastal stretch of the state. In all, information on 280 trawl hauls were collected from the logbooks provided to fishers. The information collected onboard consisted of date, depth of shooting and hauling of the net, geolocation of fishing operation, time of shooting and hauling of the net, mesh size (cod end), total catch (kg), total Indian squid catch (kg) and number of hauls per day (Dineshbabu et al. 2012). The haul duration ranged from 3 to 4 hours per haul. The collected data were brought to the GIS platform. Catch of Indian squid was normalized in terms of Catch per Hour (CPH) using the formula:

$$CPH = Ct / (th - ts)$$

Where Ct is catch of Indian squid (in kg), th = time of haul, ts = time of the net shooting.

The data collected were grouped into months and four pre-determined seasons; winter (December to February), pre-monsoon (March to May), monsoon (August to September) and post-monsoon (October -November). The fishery was closed during June and July months and hence there is no data relating to this period. The dataset (n = 280) were randomly grouped into training and test dataset. The seasonal mean geographic centres of fishing efforts were calculated using “Measuring Geographic Distribution” toolset in the spatial statistical toolbox of ArcGIS 10.1.

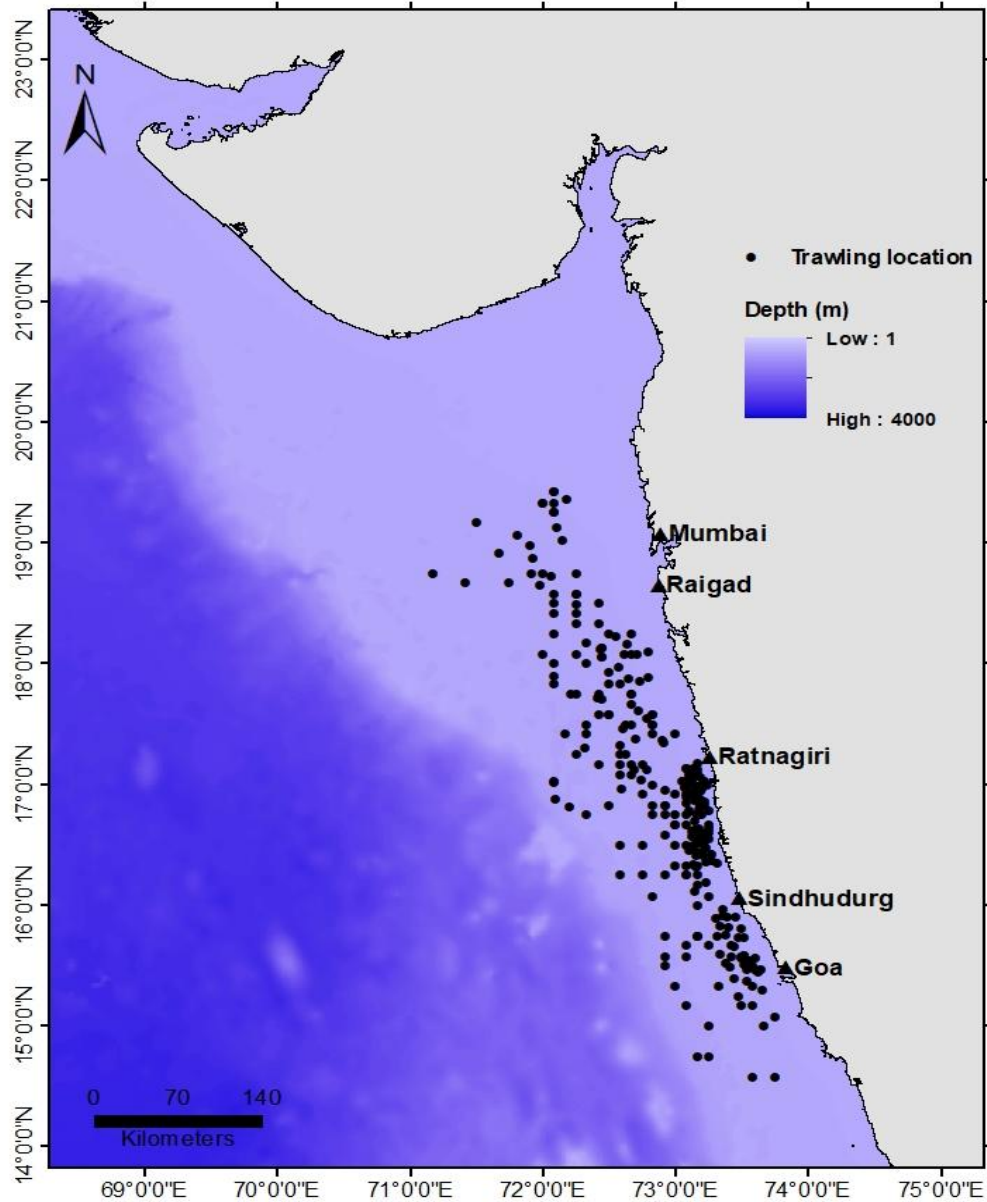


Fig. 1 Trawl geolocation during the study period northeastern Arabian sea

Remotely sensed environmental data

The selections of biophysical environmental variables for spatio-temporal distribution and habitat mapping were based on squid behaviour and previous studies in which the environmental variables were identified to influence squid/cephalopod distribution and abundance (Augustyn 1990, 1991; Sauer et al. 1991; Roberts and Sauer 1994; Guerra and Rocha 1994; Pierce et al. 1994; Balguerías et al. 2000; González et al. 2005; Otero 2006; Guerra 2006, Solanki et al. 2015). In the present study, Sea Surface Temperature (SST), Sea Surface Height (SSH), Chlorophyll-a (Chl-a), Salinity (Sal), diffuse attenuation coefficient at 490 nm (K_d_{490}), Photosynthetically Active Radiation (PAR), Ocean Current (OC) and Wind were selected to characterize environmental condition around fishing grounds of the Indian squid.

SST

The SST (°C) was derived from Advanced Very High-Resolution Radiometer (AVHRR) onboard NOAA polar-orbiting satellites pathfinder daily dataset with 4 km mapped to an equal-area projection. The present retrieval algorithms for SST from AVHRR were based largely upon the multi-channel sea surface temperature (MCSST) algorithm (McClain et al. 1985) which may be written as:

$$SST = \alpha_1 + \alpha_2 T_4 + Y(T_4 - T_5)$$

where α_1 and α_2 are constants determined through a least-squares fit to in-situ data, T_4 , T_5 , were brightness temperatures as derived from AVHRR thermal infrared channels, i.e. Ch #4 (10.3–11.3 μm) and Ch #5 (11.5–12.5 μm) channels 4 and 5 and Y is a weighting factor based on the knowledge of known absorption coefficients (Emery et al. 1994).

SSH

The SSH (m) relative to the geoid (mean ocean surface of the earth if the ocean is at rest) was derived from satellite different altimeter measurements. The altimeter measures the time taken by a radar pulse to travel from the antenna to the surface and back to the receiver. Combined with precise location data, the altimetry measurements yield sea-surface heights. The different altimeter data like TOPEX, ERS, JASON-1, JASON-2, Saral AlTiKa, etc. were processed by the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO).

Chl-a

The daily Chl-a (mg m^{-3}) was measured using an empirical relationship derived from in situ measurements of chlor_a and remote sensing reflectances (R_{rs}) in the blue-to-green region wavelengths between 440 and 670 nm of the visible spectrum in Moderate Resolution Imaging Spectroradiometer sensor (MODIS) Aqua. Presently the default chlorophyll algorithm (chlor_a) employs the standard OC3/OC4 (OCx) band ratio algorithm merged with the colour index (CI) of Hu et al. (2012).

Kd₄₉₀

A diffuse attenuation coefficient for downwelling irradiance at 490 nm (K_{d490}) in m^{-1} was calculated using an empirical relationship derived from in situ measurements of K_{d490} and blue-to-green band ratios of remote sensing reflectances (R_{rs}) near 490 nm and between 547 and 565 nm of MODIS Aqua at 4 km spatial resolution.

PAR

Frouin et al. (2003) defined PAR as the quantum energy flux in the spectral range of 400–700 nm from the sun. The MODIS Aqua PAR level-3 product with a 4 km spatial resolution has been acquired. It was calculated using the following formula;

$$PAR = \frac{1}{hc} \int_{400}^{700} \lambda E_d(\lambda, 0^-) d\lambda$$

where h is Planck's constant, c is the speed of light, and $E_d(\lambda, 0^-)$ is spectral downwelling irradiance just below the sea surface. The $E_d(\lambda, 0^-)$ was derived by attenuating extra-terrestrial solar irradiance at each sensor wavelength through the atmosphere using the derived atmospheric correction model.

Salinity

The salinity (ppt) was obtained from HYbrid Coordinate Ocean Model (HYCOM) with $0.08^\circ \times 0.08^\circ$ resolution. As part of the U. S. Global Ocean Data Assimilation Experiment (GODAE)

HYCOM consortium is a multi-institutional effort sponsored by the National Ocean Partnership Program (NOPP) to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model.

Current

The surface current (m s^{-1}) values were also obtained from HYbrid Coordinate Ocean Model (HYCOM) with $0.08^\circ \times 0.08^\circ$ resolution.

Wind

The surface wind (m s^{-1}) data was obtained from Advanced SCATterometer (ASCAT). NOAA uses ASCAT wind retrieval processing system which was developed by the KNMI scatterometer team. The ASCAT provides daily-averaged gridded wind speed, zonal component, meridional component, wind stress and the corresponding components at global scale with 0.250 resolution.

Table 1 shows the different sensors, datasets, and their resolution that were used in species habitat modelling

Table 1 Different sensors, datasets and their resolution used in habitat modelling

Parameter	Unit	Resolution	Sensor/Model
SST	$^\circ\text{C}$	Daily / 4 km	AVHRR
SSH	m	Daily / $0.25^\circ \times 0.25^\circ$	Multiple altimeter (AVISO)
Chl a	mg/m ³	Daily / 4 km	MODIS Aqua
Kd490	m ⁻¹	Daily / 4 km	MODIS Aqua
PAR	einstein/m ² /day	Daily / 4 km	MODIS Aqua
Sal	ppt	Daily/ $0.08^\circ \times 0.08^\circ$	HYCOM
OC	m/s	Daily / $0.08^\circ \times 0.08^\circ$	HYCOM
Wind	m/s	Daily / $0.25^\circ \times 0.25^\circ$	ASCAT

The daily fishing data were overlaid on a corresponding day satellite-derived variable raster. The environment data values of the corresponding location of squid catch were extracted from a satellite-derived raster using SeaDAS 7.5.1 software.

Generalized additive modelling

The generalized additive models (Hastie and Tibshirani 1990) which are non-parametric generalization of generalized linear model was used to predict the relative abundance of Indian squid in the northeastern Arabian Sea based on estimates of abundance (CPH) and oceanographic condition occurring at trawl location. The GAMs have potential advantages over other models. The GAMs consider correlation and interaction among habitat variables and

no prior assumption is required on the functional form linking the two sets of variables, as smooth functions are used to model these relationships. It also identifies sharp thresholds and makes quantitative predictions of the abundance of the species. In the present study, using the CPH as the response variable and satellite-derived environmental variable as explanatory variables the suitable habitat of Indian squid was modelled.

To select the best predictors with different combinations, a stepwise GAM procedure was used. To avoid autocorrelation among environmental variables, the correlation matrix was used as a diagnostic for advanced analyses and one of the variables was omitted from modelling if the correlation coefficient was > 0.5 among two variables or treated as a single variable. The MGCV library in the R statistical software (R Core Team 2014) was used to fit the models. GAM models were applied with a Gaussian distribution with an identity link function. To avoid overfitting, degrees of freedom (measured as a number of knots k) allowed to the smoothing functions. Any possible model misspecification and to detect pattern validation graphs were plotted. For autocorrelation, model residuals were also checked. The minimization of Akaike Information Criterion (AIC) (Akaike 1974) and level of deviance explained (0–100%; the higher the percentage, the more deviance explained) was used to select the most suitable model. The threshold values of the environmental variable were identified using the GAM plots where the variable effect become positive. The model selected for suitable habitat mapping was:

$$\ln(\text{CPH}) = s(\text{Month}) + s(\text{Lat, Long}) + s(\text{SSH}) + s(\text{Sal}) + s(\text{PAR}) + s(\text{OC}) + s(\text{SST}) \\ + s(\text{Chl. a}) + s(\text{Depth})$$

The fitted model was applied in predictive mode to provide habitat suitability off the Maharashtra coast. The prediction raster generation was carried out using the raster package in R statistical software (R Core Team 2014). For validation of this, prediction raster testing data sets were overlaid on it and performance of model evaluated by comparing the predicted abundance (CPH) and testing data abundance. The visualization and mapping were carried out in ESRI ArcGIS.

Results and Discussion

The annual latitudinal variability in trawl fisheries for Indian squid revealed three different fishing patterns (Fig. 2). After the fishing ban from June to July, in August fishers target the Indian squid in 17°N to 16°N latitudinal range with fishing fleet concentrating in 20–40 m depth range, catching on an average $43 (\pm 30) \text{ kg hr}^{-1}$ of the Indian squid. In September, the fishing fleet moved south from 16°N to 15°N at 40–60 m depth with an average catch per hour of $49 (\pm 24) \text{ kg hr}^{-1}$. As the season advances, the trawl fishing fleet for the Indian squid became more scattered moving towards the north in the latitudinal range of 17°N to 20°N . The seasonal centre of cephalopod trawl effort concentration (central tendency indicator) in the northeastern Arabian Sea reveals spatiotemporal variability of fishing patterns for the Indian squid. During monsoon, dense fishing efforts were concentrated towards southern Maharashtra in shallow waters. The fishing efforts during post-monsoon and winter are more or less at the same location.

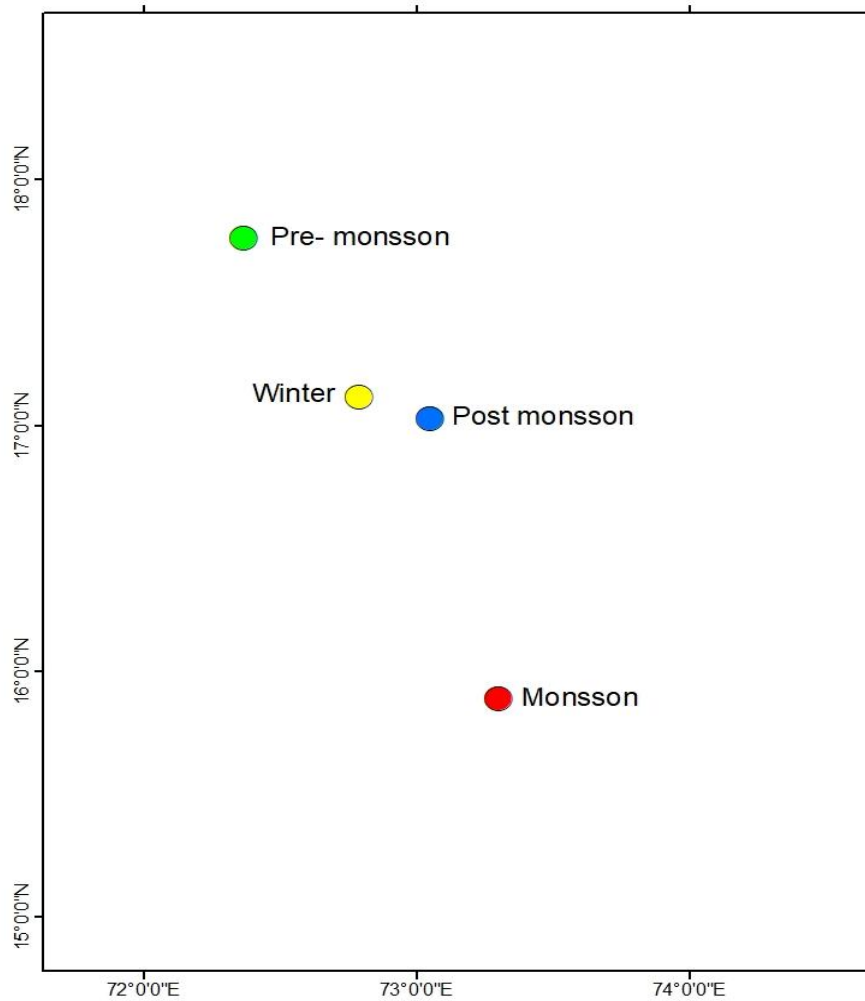


Fig. 2 Centre of trawl efforts concentration for the Indian squid off north-eastern Arabian sea

The histograms of environmental variables reveal the frequency and distribution of each variable off the north-eastern Arabian sea (Fig. 3). The optimum ranges of occurrence are indicated by a peak in the histogram. The SST frequency varies from 25.1 to 30.6° C with a mean and standard deviation of $28.01 \pm 1^\circ$ C. Most of the fishing points' frequency was distributed at 27.5 to 29.3° C. The SSH varied from -0.12 to 0.39 m (0.1 ± 0.1). The frequency of fishing catch points in the case of Chl-a was in a small range i.e. 0 to 2 mg m^{-3} . The PAR histograms show a large annual fluctuation from 8.2 to 59.6 $\text{einstein m}^{-2}\text{day}^{-1}$ with a mean of 44.5 ± 10 . Salinity has a narrow variation range in the study area (34.2-36.4 ppt). The fishing depth varies from 11-199 m with a mean and standard deviation of 61 ± 26 . Most of the fishing points' frequencies were distributed in 20 to 80 m depth.

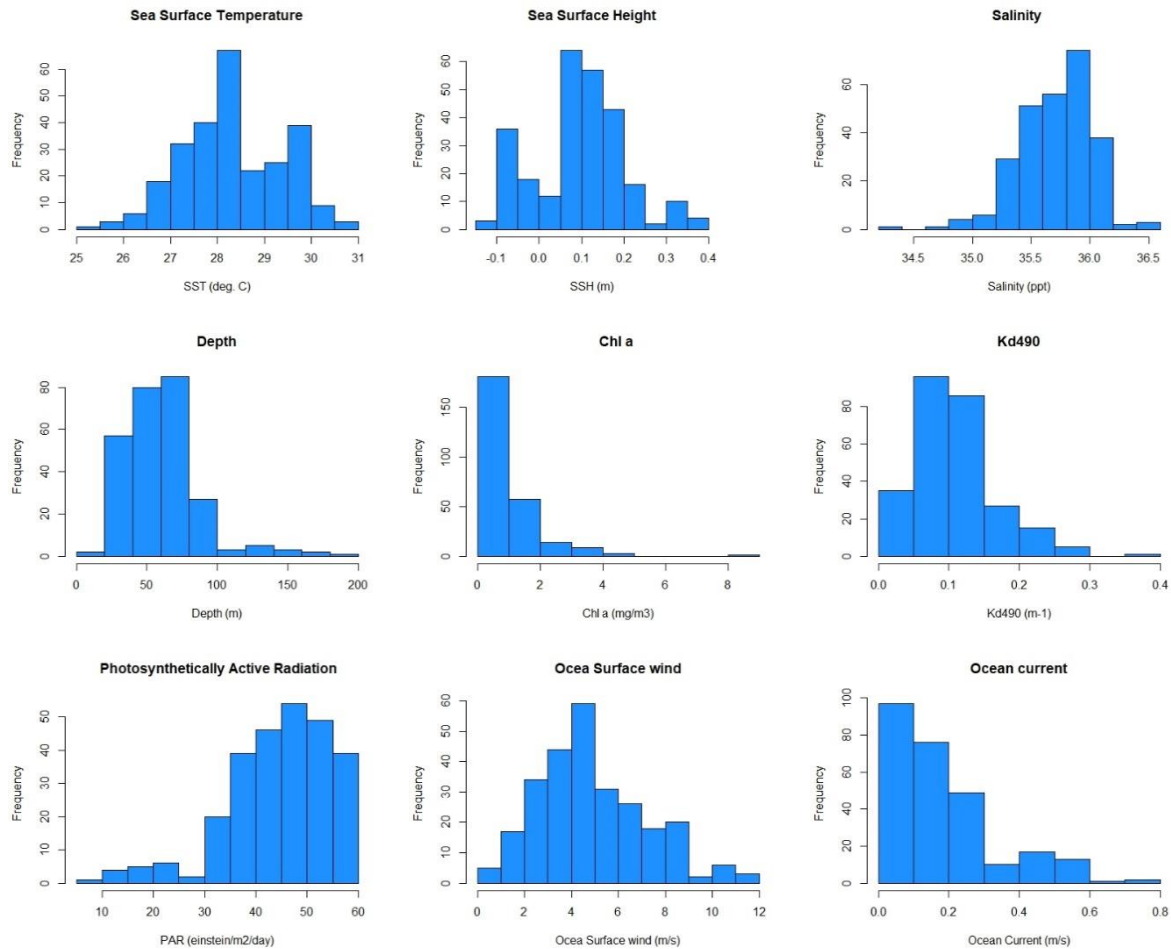


Fig. 3 The histograms showing the frequency distribution of different environmental variables

The cephalopod distribution and abundance of commercial cephalopod stocks around the world showed wide annual fluctuations. The correlation matrix gave the degree of influence of each predictor (environmental) variable on CPH of Indian squid and the collinearity between the predictor variables. The correlation matrix reveals that all the environmental variables have an additive effect on the CPH of the Indian squid. It also showed latitude and longitude are directly correlated with each other (correlation coefficient (R^2), -0.85). So, for further modelling, both were combined and treated as a single variable.

The GAM models were stepwise assessed on each variable and the combination of predictor variables. The best fit model was selected based on AIC and deviance explained by the model. The influence of each parameter (Fig. 4) showed environmental parameters such as SSH, Salinity and PAR had a major role in explaining the deviations in Indian squid abundance. The SSH anomaly indicates a nutrient-rich area which when coupled with high photosynthetically active radiation (PAR) leads to increased biological production with additive effects from other environmental parameters. Being a predator, the Indian squid may get attracted towards such productive areas. Earlier researchers have reported that *U. duvaucelii* abundance is closely associated with regions of high primary productivity, elevated chlorophyll-a concentration, and

rich zooplankton biomass, which together support dense populations of small pelagic fishes and crustaceans—the principal prey of squid (Nair et al. 1992; Mohamed 2009).

The results of fitted GAM models are shown in Table 1. The selected model with lowest AIC (607.7) and highest deviance explained (85.5%) included the spatiotemporal effect of the month, latitude, longitude, & depth and environmental effect of SSH, Salinity, PAR, OC, SST and Chl-a. The partial effect plots were generated using the selected GAM model. It showed the contribution of each smoothing function in the model, which adds up to the overall prediction. The model results indicate higher probabilities of catching the Indian squid were at locations where the SSH was ± 0.2 to 0.4 m, PAR >40 einstein $\text{m}^{-2}\text{day}^{-1}$, combined with SST in the range of 27.5 to 29.5°C , salinity 34.5 to 35 ppt, the current speed of >0.3 m s^{-1} and Chl-a > 2 mg m^{-3} . Maximum abundance of the Indian squid was found to occur between 15° to 16°N and 71.5 to 72°E .

Table 1: Summary of fitted GAM models

Model	Deviance explained (%)	AIC
$\ln(\text{CPH}) \sim \text{NULL}$	0	979.89
$\ln(\text{CPH}) \sim s(\text{Lat, Long}) + s(\text{Depth}) + s(\text{Month})$	78.9	653.54
$\ln(\text{CPH}) \sim s(\text{Lat, Long}) + s(\text{Depth}) + s(\text{Month}) + s(\text{SSH})$	78.3	656.28
$\ln(\text{CPH}) \sim s(\text{Lat, Long}) + s(\text{Depth}) + s(\text{Month}) + s(\text{SSH}) + s(\text{Kd490})$	79	656.18
$\ln(\text{CPH}) \sim s(\text{Lat, Long}) + s(\text{Depth}) + s(\text{Month}) + s(\text{SSH}) + s(\text{Kd490}) + s(\text{SST})$	80.5	643.77
$\ln(\text{CPH}) \sim s(\text{Lat, Long}) + s(\text{Depth}) + s(\text{Month}) + s(\text{SSH}) + s(\text{Kd490}) + s(\text{SST}) + s(\text{Chl.a})$	80.7	641.81
$\ln(\text{CPH}) \sim s(\text{Lat, Long}) + s(\text{Depth}) + s(\text{Month}) + s(\text{SSH}) + s(\text{Kd490}) + s(\text{SST}) + s(\text{Chl.a}) + s(\text{Sal}) + s(\text{PAR}) + s(\text{OC}) + s(\text{Wind})$	81.4	693.21
$\ln(\text{CPH}) \sim s(\text{Lat, Long}) + s(\text{Depth}) + s(\text{Month}) + s(\text{SSH}) + s(\text{SST}) + s(\text{Chl.a}) + s(\text{Sal}) + s(\text{PAR}) + s(\text{OC})$	85.6	607.70

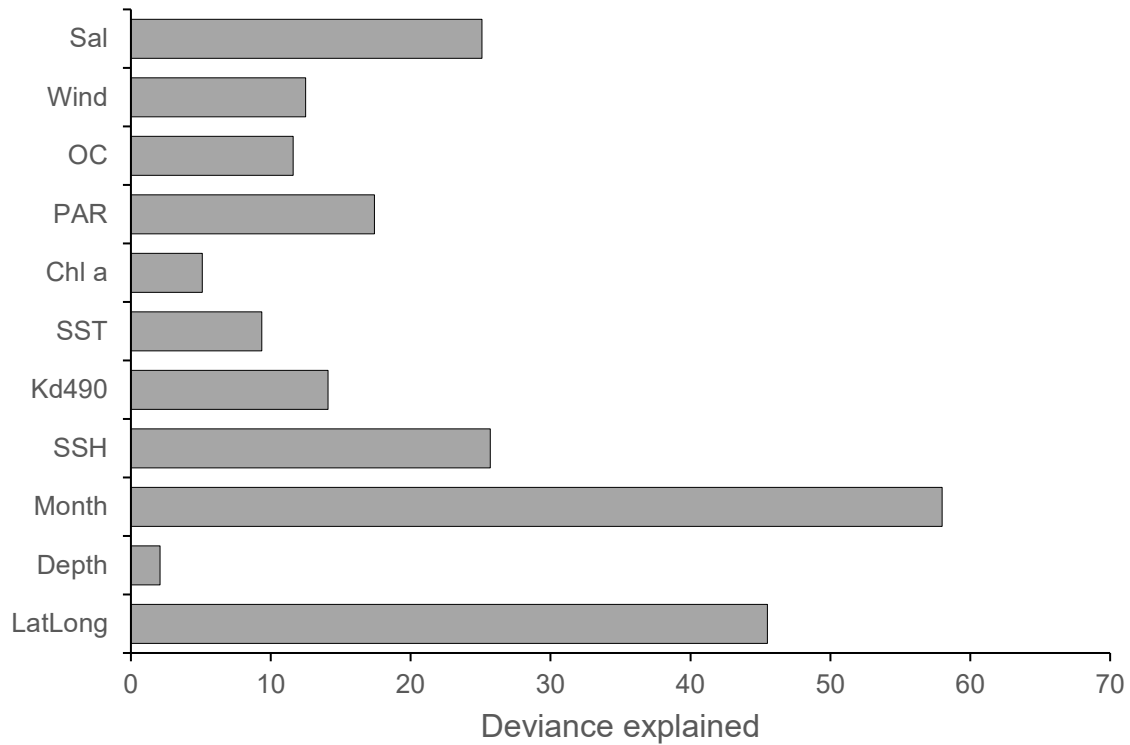


Fig. 4 The influence of different variables on abundance of the Indian squid

Based on the selected GAM model, habitat suitability raster's were prepared for the different seasons (Fig. 5) and subsequently, overall habitat suitability (Fig. 6) maps were prepared, summarizing the probability of Indian squid abundance off north east Arabian sea. During the monsoon (August to September) and post-monsoon season, the Indian squid shows nearshore abundance along the entire coastal stretch of Maharashtra. Southern Maharashtra below the Ratnagiri shows suitable habitat for Indian squid in terms of environment, time and space as the area shows abundance in all seasons. About 15 CPH points were randomly selected to validate the predictive performance of the fitted model. These points were plotted with proportional CPH values on the habitat suitability map. It was observed that the model predicted a high abundance area coinciding with a high CPH value of test data (Fig. 6).

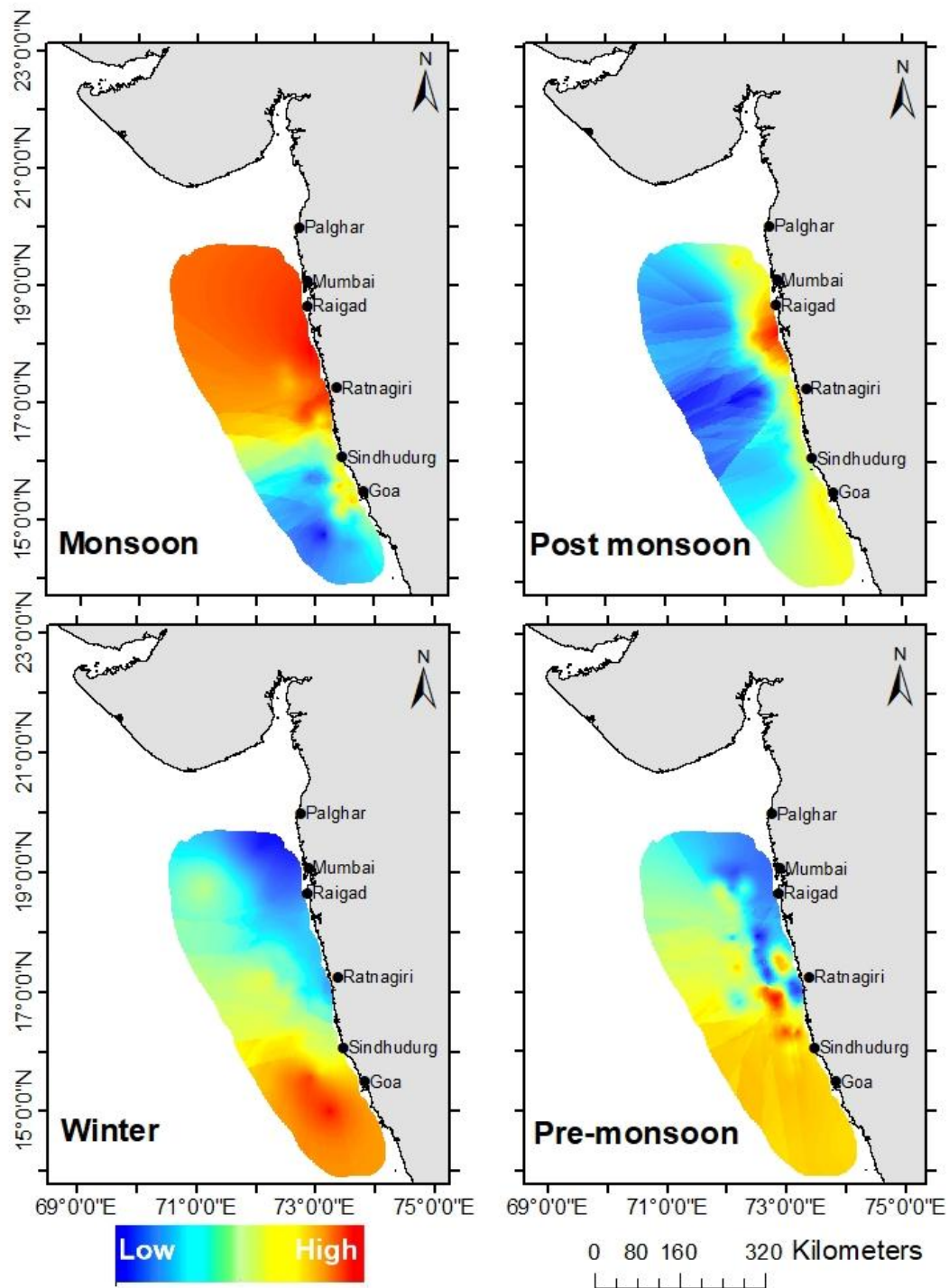


Fig. 5 Predicted seasonal habitat suitability map of the Indian squid along the North-East Arabian Sea

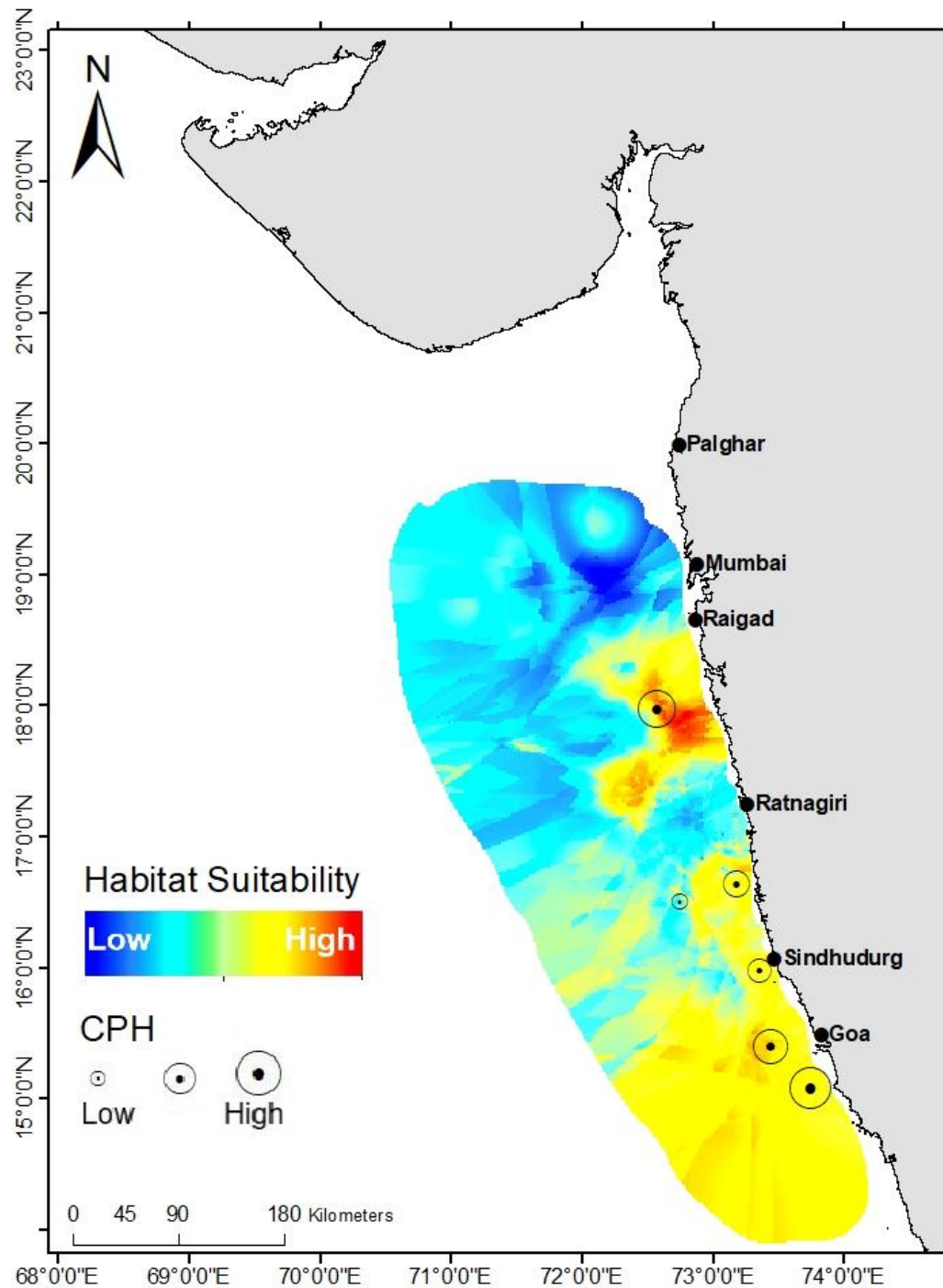


Fig. 6 Habitat suitability map for the Indian squid along the North-East Arabian Sea. The circle indicates CPH at testing data point location.

This study highlights how closely the distribution of the Indian squid *Uroteuthis (Photololigo) duvaucelii* in the northeastern Arabian Sea is tied to the seasonal rhythm of the monsoon. Rather than remaining in fixed locations, squid populations along the Maharashtra coast shift

in space and time as ocean conditions change after the southwest monsoon. These movements reflect a broader pattern that characterizes the Arabian Sea, where marine life, productivity, and fishing activities are strongly shaped by seasonal atmospheric forcing. The post-monsoon concentration of squid in southern parts of the study area, followed by their gradual spread northward, appears to be a response to the recovery and redistribution of coastal productivity. After the monsoon, enhanced mixing and circulation create favourable feeding conditions, which squid seem to track closely. Similar seasonal movements have been noted in earlier studies from the eastern Arabian Sea and point to a well-established link between monsoon processes and squid availability (Mohamed 2009; Sasikumar et al. 2018). These ecological patterns are also reflected in fishing practices, as fishers adjust their operations to follow productive grounds, illustrating the tight connection between environmental change and human livelihoods in this region. Among the environmental factors examined, sea surface height anomalies and photosynthetically active radiation stood out as particularly important. In the Arabian Sea, variations in sea surface height often signal the presence of eddies and frontal systems that help concentrate nutrients and support biological production. When such features coincide with high light availability, they create productive feeding grounds that attract squid, which depend heavily on vision for hunting. Similar relationships between squid distribution and productivity-related oceanographic features have been observed elsewhere in the Arabian Sea and in other monsoon-influenced systems, suggesting that these processes operate at broader spatial scales. The relatively narrow temperature range associated with high squid abundance indicates that *U. duvaucelii* occupies a specific thermal niche within tropical shelf waters. Unlike oceanic squid species that range widely across the Arabian Sea and tolerate a broader range of conditions, Indian squid appear to be more closely tied to stable shelf environments. Their preference for moderate salinity further supports this view, pointing to habitats shaped primarily by post-monsoon mixing rather than by strong freshwater influence.

The positive link between squid abundance, chlorophyll-a concentration, and current speed emphasizes the importance of food availability in determining where squid occur. Areas with higher productivity tend to support more zooplankton and small pelagic fishes, which form the main prey of Indian squid (Nair et al. 1992). In the highly variable Arabian Sea, such productive patches are unevenly distributed, and squid appear to respond quickly by aggregating where feeding conditions are most favourable. More broadly, the strong seasonal signal captured by the model reflects the life-history traits of squid themselves. With short life spans, rapid growth, and limited capacity to buffer environmental variability, squid respond swiftly to changing ocean conditions (Rodhouse 2001). As a result, their distribution provides a sensitive indicator of ecosystem dynamics in the Arabian Sea, particularly in a period when monsoon patterns and marine environments are undergoing change. By identifying how environmental conditions shape squid habitat, this study contributes to a growing effort to understand the Arabian Sea as a coupled human–environment system. Squid abundance is not simply a biological outcome but the result of interactions between monsoon-driven oceanography, ecological productivity, and fishing behaviour. Viewing squid fisheries through this integrated lens is especially important in the Arabian Sea, where environmental variability, resource use, and coastal livelihoods are closely intertwined.

Conclusion

The habitat suitability models have popularly become an effective technique to identify factors influencing species occurrence and later visualize the spatial distribution of suitable habitats on the GIS platform for sustainable management. The fitted habitat suitability model indicates higher probabilities of finding Indian squid in areas where SSH is ± 0.2 to 0.4 m, salinity 34.5 to 35 ppt, $PAR > 40$ einstein $m^{-2}day^{-1}$, combined with SST in range of 27.5 to $29.5^{\circ}C$, the current speed of >0.3 $m\ s^{-1}$ and $Chl-a > 2$ $mg\ m^{-3}$. A higher abundance of Indian squid lies at 15° to $16^{\circ}N$ and 71.5 to $72^{\circ}E$. The season and location were the most influential variables explaining the distribution of squids in the northeast Arabian Sea. The fitted model demonstrated the potential dynamics of suitable habitat for the Indian squid along the northeastern Arabian Sea. Such habitat suitability studies are important for assessing the distribution and abundance of fishes on a synoptic scale. Considering the annual nature of the Indian squid fishery, such studies should be carried out regularly for sustainable exploitation of the species.

Acknowledgements

We express our sincere gratitude to the Director, ICAR-Central Marine Fisheries Research Institute, Kochi for providing constant support and required facilities for the work.

Author Contributions S.N.B Conceptualization, Data collection, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing and K.S.M. Conceptualization, Supervision, Methodology, Validation, Writing – review & editing and L.S. Supervision, Writing – review & editing and A.S. Data collection, Writing – review & editing, A.C. and A.D.N. and A.K.V. and R. K. R. and Z. P. U. Writing – review & editing

Funding This work was carried out under the project National Innovations in Climate Resilient Agriculture - Marine Fisheries receiving funding support from the Indian Council of Agricultural Research.

Data Availability Data available from authors on request.

Declarations

Ethical Approval This article does not contain any experimental studies and no formal ethical approval is required.

Competing interests The authors declare no competing interests.

Clinical Trial Number Not applicable

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