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BILLFISH FISHERIES IN INDIA WITH INSIGHTS INTO THE HABITAT PREFERENCE AND BIOLOGY OF SWORDFISH (XIPHIAS GLADIUS) FROM THE WESTERN INDIAN EEZ

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Purpose, expectation and action intended (select one or more and include corresponding text)

Discussions (for information and open discussion):

The paper is to inform meeting members of the ten-year (2016–2025) trends and species composition of India's billfish landings, the environmental drivers of swordfish habitat suitability, and the length-weight relationship and length at first maturity of swordfish in Indian waters.

Feedback (to collect input and suggestions)

Not applicable

Conclusion (to record a concluded position or summary)

Not applicable

Recommendation (to ask the meeting to endorse a recommendation)

The paper is to seek endorsement of the recommendation that future management and conservation measures for India's billfish resources explicitly account for the predominantly coastal nature (traditional) of the fishery and be underpinned by continued, effort-standardised, species-resolved data collections.

Billfish Fisheries in India with insights into the Habitat Preference and Biology of Swordfish (*Xiphias gladius*) from the Western Indian EEZ

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Abstract

Billfishes support economically important artisanal, commercial, and recreational fisheries along the Indian coast, yet long-term assessments of their landings remain limited. This study analysed ten years (2016–2025) of landing statistics to evaluate temporal trends and species composition of Indian billfish fisheries. Sailfish (*Istiophorus platypterus*) dominated the landings, averaging 7,932 ± 794 t year^{-1}, followed by swordfish (*Xiphias gladius*) with 2,079 ± 239 t year^{-1}, and sailfish landings were significantly higher than swordfish throughout the study period (paired t-test, $p < 0.0001$). No significant long-term temporal trend was detected for either species despite marked interannual variability. Generalized Additive Model analysis showed that sea surface salinity (SSS), sea surface temperature (SST), sea surface height anomaly (SSHa), and current speed significantly influenced swordfish catch rates ($p < 0.05$), whereas chlorophyll-a was not significant, and the model explained 45.5% of the variation in catch rates. Swordfish exhibited higher habitat suitability in waters with SST of 25–29 °C, salinity of 32–37 ppt, positive SSHa (>4 m), and current speeds below 0.2 m s^{-1}, providing valuable information for habitat prediction, fisheries management, and sustainable exploitation of billfish resources in Indian waters. The lower jaw fork length (LJFL) of swordfish analysed between 2022-2025 ranged from 57.7 to 294.8 cm, with a mean of 135.8 cm, while body weight varied from 3.5 to 132.7 kg (mean: 22.6 kg). The length–weight relationship of swordfish was highly significant (R^2 = 0.876, $P < 0.001$) and was described by the equation $W = 2.27 \times 10^{-6} L^{3.131}$, with the allometric coefficient ($b = 3.131$) not differing significantly from the theoretical isometric value of 3 ($P = 0.15$), indicating isometric growth.

Keywords: billfish; sailfish; swordfish; landings trend; India; EEZ

1. Introduction

Billfishes includes the marlins, sailfish, and swordfish of the families *Istiophoridae* and *Xiphiidae* are large, highly migratory epipelagic predators that support valuable commercial, artisanal, and recreational fisheries throughout the tropical and subtropical oceans of the world (Nakamura, 1985). Despite their ecological and economic importance, most billfish stocks are subjected to substantial fishing pressure, and the status of many populations remains uncertain because of incomplete catch reporting. Sailfish were classified as “Vulnerable” on the IUCN Red List in 2022, while population trends for most other billfish species have been assessed as either decreasing or data deficient (Collette et al., 2022). Fishing mortality results from both targeted commercial and artisanal fisheries and incidental capture as bycatch in tuna longline and purse-seine fisheries (Pons et al., 2017; Sharma et al., 2018).

Along the Indian coast, billfish principally sailfish, swordfish, and several marlin species form part of the wider tuna-and-allied resource complex landed by a diverse coastal fishery that contributes substantially to India's overall marine fish landings. The present study uses ten years (2016–2025) of official India-level billfish landings statistics, disaggregated into six categories, sailfish, swordfish, blue marlin, black marlin, striped marlin, and Marlin spp. to (i) describe the magnitude and inter-annual variability of landings by species, (ii) test for statistically detectable temporal trends using both parametric and non-parametric methods, (iii) examine whether the species composition of the catch differs significantly among categories, and (iv) explore the degree of co-variation among species as an indicator of shared environmental drivers.

Habitat preference is a fundamental ecological characteristic that governs the spatial distribution, migration patterns, feeding ecology and reproductive behaviour of marine organisms. In highly migratory pelagic fishes such as billfishes (Family: Istiophoridae and Xiphiidae), habitat selection is a dynamic process driven by the interaction of environmental conditions and biological requirements. Unlike coastal fishes inhabiting relatively stable environments, billfishes occupy highly variable pelagic ecosystems where oceanographic conditions fluctuate over multiple spatial and temporal scales. Consequently, their distribution is closely associated with favourable environmental conditions that maximize prey availability while minimizing energetic costs associated with migration and foraging (Shimose et al., 2010; Block et al., 2011).

Among the environmental variables influencing habitat preference, sea surface temperature (SST) has consistently been identified as one of the most important determinants of billfish distribution. Likewise, sea surface height anomaly (SSHa), an indicator of mesoscale circulation, identifies cyclonic and anticyclonic eddies that influence nutrient transport and biological productivity, while current velocity affects prey aggregation, larval transport and migration pathways. (Su et al., 2011). Chlorophyll-a concentration is frequently incorporated into habitat preference studies as a proxy for primary productivity. However, its relationship with billfish occurrence is often indirect because large pelagic predators generally respond to the distribution of secondary consumers rather than to phytoplankton biomass itself. Several studies have demonstrated that combinations of SST, SSS, SSHa, chlorophyll-a and current systems explain habitat preference more effectively than individual environmental variables considered independently.

Coupling remotely sensed oceanographic information with fisheries catch and effort data has enabled researchers to quantify species environment relationships and predict favourable habitats with greater accuracy. Among various statistical approaches, Generalized Additive Models (GAMs) have become one of the most widely used methods because they effectively capture nonlinear ecological responses without imposing restrictive parametric assumptions. GAMs have successfully identified environmental thresholds governing habitat selection in numerous pelagic fishes, including tunas, swordfish and sailfish, thereby providing robust tools for habitat suitability mapping and prediction (Surya et al., 2022).

Identifying the environmental drivers governing habitat selection not only improves ecological understanding of billfish distribution but also contributes to habitat suitability modelling, prediction of potential fishing grounds, ecosystem-based fisheries management and conservation planning. Such information is essential for developing adaptive management strategies aimed at ensuring the sustainable utilization of billfish resources in rapidly changing marine ecosystems.

2. Materials and Methods

2.1 Data compilation

Annual species-wise billfish landings (in tonnes) for India for the years 2016–2025, compiled from India's National Reports submitted to the Indian Ocean Tuna Commission (IOTC) for the corresponding years (Government of India, 2016–2025), were compiled for six categories: sailfish (*Istiophorus platypterus*), swordfish (*Xiphias gladius*), blue marlin (*Makaira nigricans*), black marlin (*Istiompax indica*), striped marlin (*Kajikia audax*), and unidentified Marlin spp.

Sailfish and swordfish, which were landed in every year of the study period and together comprised the great majority of billfish catch, were used for all inferential trend and regression analyses. Blue marlin, black marlin, striped marlin, and Marlin spp. were landed intermittently, with true zero catch in six to nine of the ten years for the individually identified marlin species.

2.2 Distributional analysis

For sailfish and swordfish, the following descriptive statistics were computed for the 2016–2025 series: sample size, mean, median, standard deviation, standard error, minimum, maximum, range, coefficient of variation (CV), first and third quartiles, interquartile range (IQR), and the 95% confidence interval of the mean (Student's t distribution, df = 9).

2.3 Trend and regression analysis

Two complementary trend-detection approaches were applied to the sailfish and swordfish series independently: (i) ordinary least-squares linear regression of landings on calendar year, from which the slope, its standard error, 95% confidence interval, coefficient of determination (R^2), adjusted R^2, and overall F-test p-value were obtained; and (ii) the non-parametric Mann–Kendall trend test (Mann, 1945; Kendall, 1975), which does not assume linearity or normality, together with the associated Theil–Sen slope estimator (Sen, 1968), computed using the pymannkendall package. Compound annual growth rate (CAGR) and year-on-year percentage change were computed descriptively to characterise the magnitude and volatility of interannual change independently of formal trend significance.

2.4 Relationship between species and comparative testing

The linear association between sailfish and swordfish annual landings was quantified using Pearson's product-moment correlation coefficient. Because sailfish and swordfish landings were recorded for the same ten years, a paired experimental design was used to test whether the two species differed systematically in landed quantity: a paired t-test (justified by the Shapiro–Wilk normality results reported in the Results) and as a distribution-free cross-check, the Wilcoxon signed-rank test were applied to the ten paired annual differences, with Cohen's d computed as the standardised effect size.

The available dataset consisted of a single aggregate annual landings value for each species, with no replicate observed within a year. Consequently, a classical one-way ANOVA comparing annual landings among years was not appropriate, as each year contributed only one observation per species. Instead, two comparative analyses that were consistent with the structure of the dataset were performed. First, differences in annual landings among the six billfish species/categories were evaluated using the Kruskal–Wallis H-test, treating the ten annual observations within each species/category as replicates. The Kruskal–Wallis test was selected in preference to one-way ANOVA because four of the six species/categories contained multiple zero values and violated the assumption of normality. Effect size was quantified using eta-squared (η^2). Where significant differences were detected, pairwise comparisons were conducted using Dunn's post hoc test with Bonferroni correction to control for multiple testing.

Geospatial Analysis

Data regarding the date, time, speed of the boat and geospatial data of each point of shooting and hauling of all operations were collected. A base map of India with a WGS84 coordinate reference system showing the coastline was used for the study. The data were interpreted with GIS-based software package (ArcGIS 10.3 and QGIS 3.44) to spatially interpolate and demarcate the fishing ground and spatio-temporal variation in the catch. For interpolation, the Inverse Distance Weighted (IDW) method was used. The IDW interpolator assumes that each input point has a

Parameter	Data Source	Resolution

local influence that

diminishes with distance, such that the variable being mapped decreases in influence with distance from its sampled location.

Environmental sampling

Satellite-derived environmental parameters were collected from Internet-based Earth Observation portals like NASA Internet servers Ocean Color Web (https://oceancolor.gsfc.nasa.gov/), Copernicus Marine Environment Monitoring Service (https://marine.copernicus.eu/) (CMEMS), Physical Oceanography Distributed Active Archive Center (https://podaac.jpl.nasa.gov/) and INCOIS live access server (http://las.incois.gov.in/). The value was extracted for each fishing geo-location by using Sentinel Application Platform (SNAP) software. These data were tabulated in an Excel sheet making it compatible for analysis. The oceanographic parameters such as temperature, current speed, chlorophyll, salinity and bathymetry can be integrated into the GIS software routine for correlation studies. The data on SST, SSS, Chl-a, Current Speed, and SSHa were collected from the product of the Copernicus Marine Environment Monitoring Service (CMEMS; marine.copernicus.eu) under the Copernicus Marine Service Licence (http://marine.copernicus.eu/services-portfolio/service-commitments-and-licence/) (Table 1). The Copernicus Marine Environment Monitoring Service (CMEMS) provides Level-4 (i.e. variables generated from various measurements) reprocessed and multi-sensor merged satellite-derived environmental parameters. Multiple layers of information in GIS routine help to predict the fishery distribution, especially in terms of environmental parameters. To generate the theme map, India's geo-referenced base map with World Geodetic System (WGS) coordinate reference system was used and the maps were generated in ArcGIS (Version 10.3, licensed to CIFE).

Sea Surface chlorophyll	E.U. Copernicus Marine Service Information	0.083°x 0.083°
Sea Surface Temperature	E.U. Copernicus Marine Service Information	0.083°x 0.083°
Sea Surface Salinity	E.U. Copernicus Marine Service Information	0.083°x 0.083°
Current speed	E.U. Copernicus Marine Service Information	0.5° x 0.5°
Sea Surface Height	E.U. Copernicus Marine Service Information	0.083°x 0.083°

Table.1. Data sources of environmental parameters used in the present study

Statistical analysis, Estimation of relationship between oceanographic parameters and billfish catch rates

GAM is a traditional ecological model used to predict the potential fishing grounds of marine fishes (Al-Kharusi, 2008; Brodie et al., 2015; Solanki et al., 2016). The predictor variables included in the model were SST, SSS, CHL, Current speed and SSHa. These predictor environmental variables were chosen as they had wide spatial coverage throughout the study region. The GAM approach (Hastie and Tibshirani, 1990) was used to predict the relative abundance of billfish functional groups across the entire fishing location.

The relationship between a response variable (Y) and independent variables (or predictors) is given by the formula Y = link linear predictor (LP) and

$LP = \alpha + \sum fi\ (Xi) + \varepsilon$

Where, LP is the linear predictor, the link function is a transformation used to accommodate different response distributions, α is the intercept and ε is the error term. The 'fi' is smooth functions, estimated individually for each predictor (Xi) (SST, SSHa, Current speed, Chl-a and SSS). All models were fit using the 'mgcv' package in the R version 4.0.3 environment. The test dataset was used as independent data to predict the catch using the final model constructed with the training dataset. Models of catch rates that incorporate relevant environmental variables can be used to infer possible responses in the distribution of billfishes. These functional relationships can be used to evaluate the impacts of environmental variability on the spatial pattern of billfishes. The selected model had the lowest Akaike's Information Criteria (AIC) and expressed as:

$Yi = \alpha + s(SSS) + s(SST) + s(SSHa) + s(current) + s(Chl\text{-}a) + \varepsilon i$

Where Yi is the response variable (Catch rate), α is the intercept, f (Xi) is the explanatory variable with a smoothing function, Xi is the explanatory (continuous) variable and εi is the residual or information that is not explained by the model. The optimal degrees or the amount of movement in the smoothing was estimated by cross-validation. The default option in the type of a smoother in mgcv is a thin plate regression spline but different smoothers according to the data can be used. For example, cyclic cubic regression spline (cc) is a useful smoother since it ensures that the value of the smoother at the far-left point of the gradient is the same as at the far-right point of the gradient. Hence, it is a useful smoother time variable. The plots of the best-fitting smooths for the effect of the covariates were presented as the GAM model results. Relative importance of each covariate of the model was shown on the y-axis. Model validations were made on the basis of numerical results and visual inspection of graphs.

Estimation of Length at First Maturity (L_{50})

The length at first maturity (L_{50}), defined as the lower jaw fork length (LJFL) at which 50% of the swordfish population attains sexual maturity, was estimated using a logistic regression model. The proportion of mature individuals was calculated for each 10-cm length class based on maturity observations. The relationship between maturity proportion and fish length was modelled using a generalized linear model (GLM) with a binomial error distribution and logit link function in R (version 4.0.3).

The logistic model was expressed as: $P = 1 / (1 + \exp(-(a+bL)))$ where P is the probability of maturity, L is the lower jaw fork length (cm), and a and b are the regression coefficients. The length at first maturity (L_{50}) was estimated as: $L_{50} = -a/b$. The fitted logistic curve was used to describe the maturity ogive and estimate the length corresponding to 50% maturity.

3. Results

3.1 Species composition over time

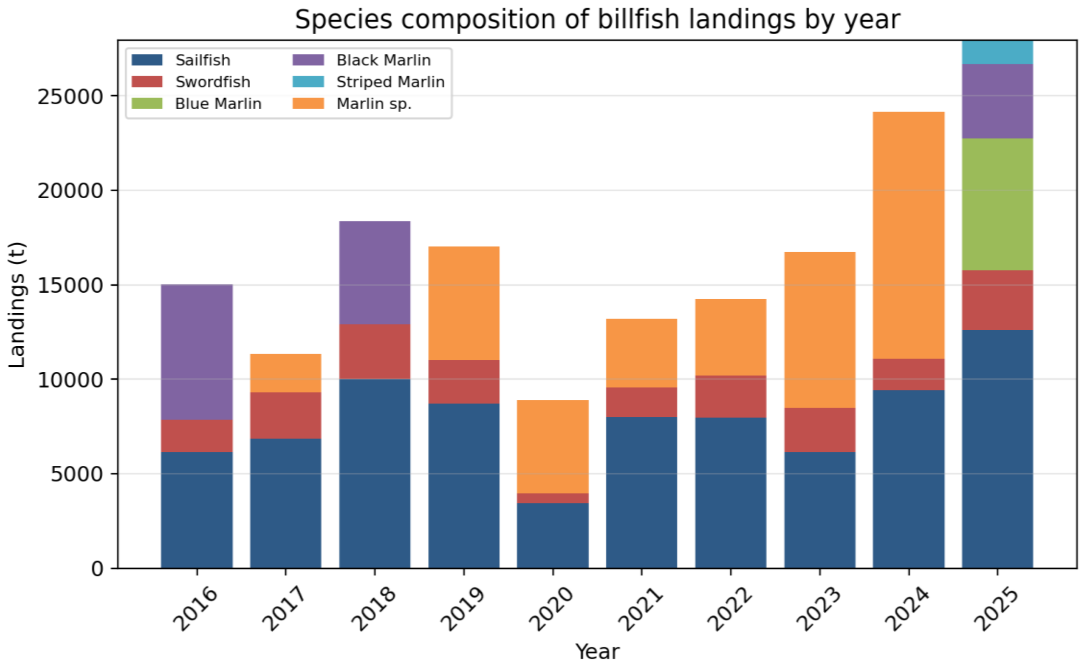

Figure 1. Stacked-bar composition of annual billfish landings by species and year from 2016 to 2025.

3.2 Descriptive statistics

Sailfish landings averaged 7,932 ± 794 t year^{-1} (95% CI: 6,136–9,727 t), ranging from 3,438 t (2020) to 12,604 t (2025), with a coefficient of variation of 31.6%. Swordfish landings averaged 2,079 ± 239 t year^{-1} (95% CI: 1,537–2,621 t), ranging from 514 t (2020) to 3,164 t (2025), with higher relative variability (CV = 36.4%). Both the sailfish and swordfish series did not depart significantly from normality (Shapiro–Wilk W = 0.982, p = 0.973 and W = 0.949, p = 0.658, respectively), supporting the use of parametric methods for the paired comparison. Levene's test indicated that the variances of the two species' landings differed significantly (F = 5.52, p = 0.030), consistent with swordfish landings being proportionally more variable than sailfish landings relative to their mean (Table 2).

Statistic	Sailfish (t)	Swordfish (t)
n (years)	10	10
Mean ± SE	7,932 ± 794	2,079 ± 239
Median	8,000	2,269
Standard deviation	2,510	757
Minimum	3,438 (2020)	514 (2020)
Maximum	12,604 (2025)	3,164 (2025)
Range	9,166	2,649
Coefficient of variation (%)	31.6	36.4
Interquartile range (Q1–Q3)	6,326–9,226	1,677–2,431
95% CI of mean	6,136–9,727	1,537–2,621
Shapiro–Wilk W (p)	0.982 (0.973)	0.949 (0.658)

Table 2. Descriptive statistics for annual sailfish and swordfish landings, India, 2016–2025 (n = 10 years each).

3.3 Relationship and comparison between sailfish and swordfish

Sailfish and swordfish annual landings were positively and significantly correlated (Pearson r = 0.77, p = 0.010; Figure 2), indicating that years of higher sailfish catch tended to coincide with years of higher swordfish catch, consistent with the two species being caught substantially in the same coastal fishing grounds.

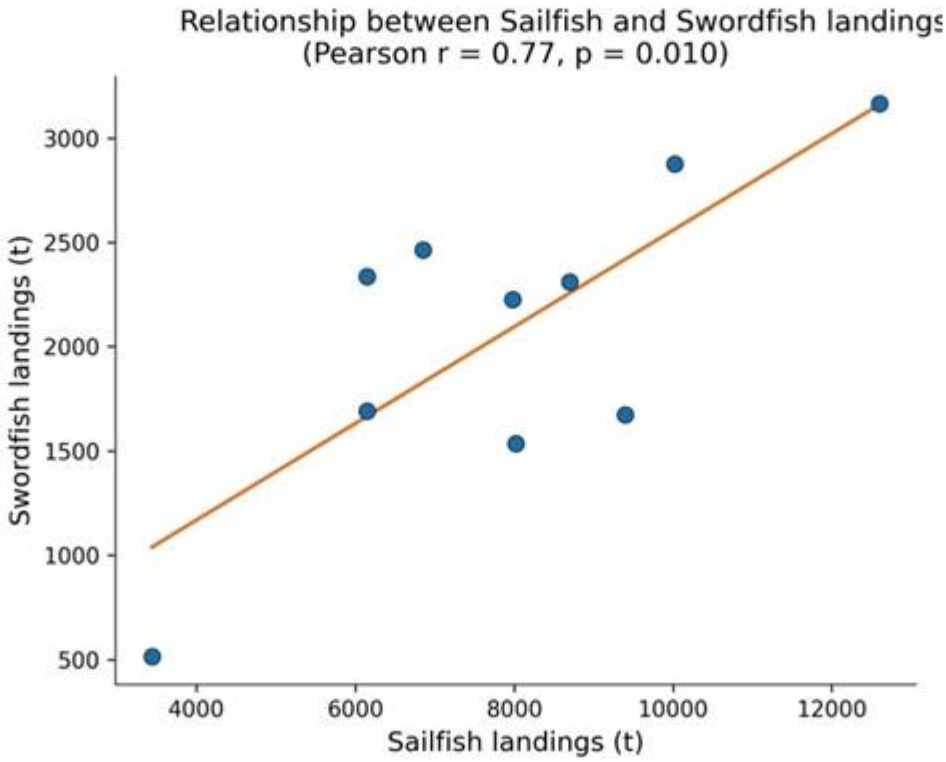

Figure 2. Relationship between annual sailfish and swordfish landings, 2016–2025, with ordinary least-squares regression line (Pearson r = 0.77, p = 0.010).

Sailfish landings consistently exceeded swordfish landings throughout the study period. The annual landing ranges of the two species did not overlap, with the minimum recorded sailfish landing (3,438 t) exceeding the maximum recorded swordfish landing (3,164 t). A paired *t*-test confirmed that sailfish landings were significantly higher than swordfish landings (mean paired difference = 5,853 t; $t(9) = 9.30$, $p < 0.0001$; Cohen's $d = 2.94$). The non-parametric Wilcoxon signed-rank test yielded the same conclusion, with sailfish landings exceeding swordfish landings in all ten years, resulting in the maximum possible signed-rank statistic ($W = 55$) and an exact two-tailed $p = 0.002$. The agreement between the parametric and non-parametric tests demonstrates that the higher sailfish landings were both statistically significant and highly consistent across the study period, irrespective of distributional assumptions.

3.4 Trend analysis

Linear regression of landings on year showed a positive but statistically non-significant slope for both species: sailfish landings increased by an estimated 358 t year^{-1} (95% CI: −252 to 967 t year^{-1}; $R^2 = 0.19$, adjusted $R^2 = 0.08$; p = 0.213), and swordfish landings increased by an estimated 35 t year^{-1} (95% CI: −158 to 228 t year^{-1}; $R^2 = 0.02$, adjusted $R^2 = -0.10$; p = 0.699). The non-parametric Mann–Kendall test corroborated the absence of a statistically detectable monotonic trend for either species (sailfish: S = 13, $\tau = 0.29$, p = 0.283, Sen's slope = 368 t year^{-1}; swordfish: S = 3, $\tau = 0.07$, p = 0.858, Sen's slope = 41 t year^{-1}).

Despite the absence of a statistically significant linear or monotonic trend, both species showed substantial interannual volatility and a marked increase in the final year of the series: sailfish landings rose from 9,401 t in 2024 to 12,604 t in 2025 (+34.1%), and swordfish landings nearly doubled, from 1,672 t to 3,164 t (+89.2%), over the same interval. Notable troughs occurred in 2020 for both species (sailfish −60.5% and swordfish −77.7% relative to 2019), coinciding with the year of COVID-19-related restrictions nationally. Compound annual growth rates over the full ten-year window were 8.3% year^{-1} for sailfish and 7.2% year^{-1} for swordfish — figures that describe the net multi-year change but, given the non-significant trend tests, should not be interpreted as evidence of a sustained, statistically reliable growth trajectory over and above high year-to-year variability.

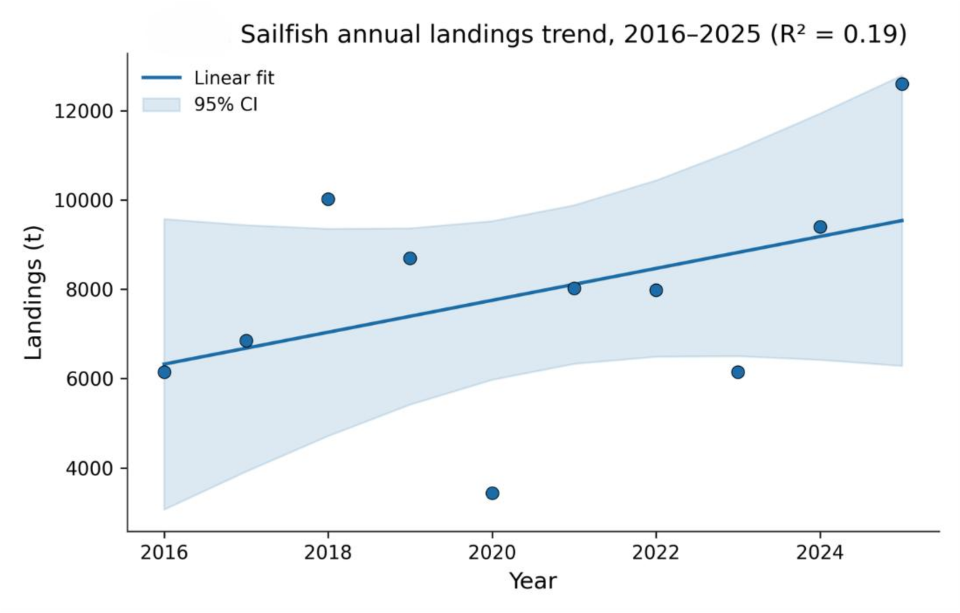

Figure 3. Sailfish annual landings, 2016–2025, with ordinary least-squares linear trend and 95% confidence band.

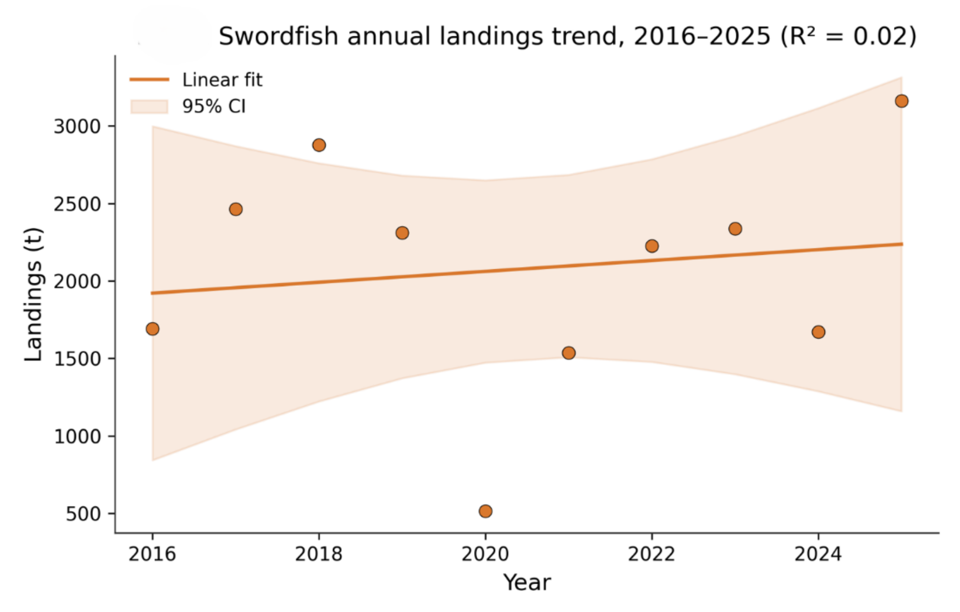

Figure 4. Swordfish annual landings, 2016–2025, with ordinary least-squares linear trend and 95% confidence band

Test	Sailfish	Swordfish
OLS slope (t yr^{-1})	357.6	35.1
OLS slope 95% CI	−252 to 967	−158 to 228

R^2 (adjusted R^2)	0.186 (0.084)	0.020 (−0.103)
OLS p-value	0.213	0.699
Mann–Kendall S	13	3
Kendall's τ	0.289	0.067
Mann–Kendall p-value	0.283	0.858
Sen's slope (t yr^{-1})	368.4	41.0
CAGR (2016–2025)	8.3%	7.2%

Table 3. Linear regression and Mann–Kendall trend statistics for sailfish and swordfish landings, 2016–2025.

3.5 Comparison among the six billfish species/categories

Across all six billfish species/categories, annual landings differed significantly (Kruskal–Wallis H = 34.15, df = 5, $p < 0.0001$; eta-squared = 0.54, a large effect), confirming that the billfish catch is not evenly distributed among species. Dunn's post-hoc test (Bonferroni-corrected) showed that sailfish landings were significantly greater than blue marlin ($p < 0.001$), black marlin ($p = 0.004$), and striped marlin ($p < 0.001$), but did not differ significantly from swordfish ($p = 0.330$) or from the aggregated Marlin spp. category ($p = 0.745$) ,the latter reflecting the fact that Marlin spp. landings, while zero in most years, reached very large single-year pulses (e.g. 13,075 t in 2024) that elevated its overall distribution to a level statistically comparable with sailfish despite its intermittent occurrence.

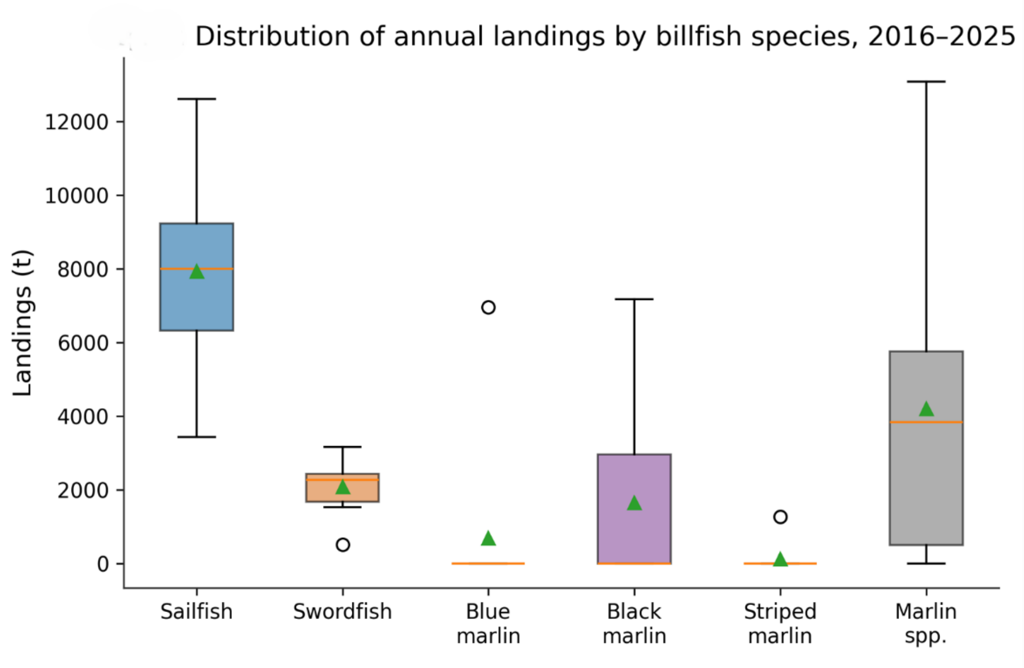

Figure 5. Distribution of annual landings (2016–2025) by billfish species/category, illustrating central tendency and interannual spread.

Comparison	Dunn's p (Bonferroni)	Significant (α = 0.05)
Sailfish vs Swordfish	0.330	No
Sailfish vs Blue Marlin	< 0.001	Yes
Sailfish vs Black Marlin	0.004	Yes
Sailfish vs Striped Marlin	< 0.001	Yes
Sailfish vs Marlin spp.	0.745	No

Table 4. Dunn's post-hoc pairwise comparisons of sailfish against the other five billfish categories

This analysis provides a decadal, statistically formalised characterisation of species-wise billfish landings dynamics along the Indian coast. Two broad patterns emerge: a persistent and statistically robust dominance of sailfish over swordfish in landed quantity, confirmed by both the paired t-test and the Wilcoxon signed-rank test; and the absence of a detectable long-term linear or monotonic trend for either species despite considerable net growth and a pronounced 2025 peak.

Absence of a statistically detectable trend, despite a 2025 peak

Neither the linear regression nor the Mann–Kendall test detected a statistically significant trend for sailfish or swordfish over 2016–2025, notwithstanding compound annual growth rates of 8.3% and 7.2% respectively and a marked increase in the final year. This apparent tension is explained by the high interannual variability in both series (CV = 32–36%) relative to the number of available annual observations (n = 10): with only ten yearly data points and a pronounced trough in 2020, the statistical power to detect a linear trend of the observed magnitude is limited, and a single high-leverage final-year value (2025) is not, by itself, sufficient evidence of a sustained directional shift. The 2020 trough coincided with nationwide COVID-19-related restrictions, offering a plausible effort-driven explanation for that particular deviation rather than a resource-driven one, while the magnitude and cause of the 2025 increase cannot be determined from landings data alone without corresponding fishing-effort information.

Species dominance and co-variation

The consistent, large-magnitude difference between sailfish and swordfish landings (paired d = 2.94) is consistent with previous descriptive accounts of the Indian billfish fishery identifying sailfish as the numerically dominant billfish species landed along the coast (Anil, 2021), reflecting its greater availability over the continental shelf, where sailfish characteristically aggregate to feed, in contrast to the more oceanic distribution of swordfish (Nakamura, 1985). The significant positive correlation between the two species' annual landings (r = 0.77) is consistent with substantial co-capture in the same fishing grounds.

Species composition differences

The Kruskal–Wallis comparison confirmed that landings differ significantly among the six billfish categories, with sailfish landings statistically indistinguishable from the aggregated Marlin spp. category despite the latter's intermittent occurrence, a result driven by very large single-year Marlin spp. pulses that are not separately resolved to blue, black, or striped marlin. This pattern is most parsimoniously interpreted as reflecting inconsistencies in species-level identification and reporting at landing centres across years, rather than necessarily indicating a genuine ecological pattern; it cannot be confirmed from the aggregated national data used here and would require verification against landing-centre-level records.

Building on these findings, we recommend: (i) continued and, where possible, extended time-series monitoring of species-wise billfish landings to improve the statistical power of future trend analyses; (ii) collection and integration of standardised fishing-effort data to enable calculation of CPUE and more defensible inference about relative abundance; (iii) targeted training and protocol review for landing-centre enumerators to reduce the proportion of catch recorded only as unidentified Marlin spp.; (iv) a formal reconciliation of the species-wise recording systems to prevent recurrence of reporting shortfalls of the kind noted above; and (v) longer-term integration of biological and, where feasible, genetic stock-structure information, following the approach of recent global sailfish population-genetic studies (Smith et al., 2025), to inform whether India's sailfish and swordfish landings should be considered part of a wider Indian Ocean management unit or evaluated with reference to more localised population structure.

Habitat preference of billfish with special reference to Swordfish.

The best GAM with the lowest Akaike's Information Criteria (AIC) for *X.gladius* was of the following form; X. *gladius* ~ s(SSS, k = 3) + s(SST, k = 3) + s(SSHa, k = 3) + s(current, k = 3) + s(Chl-a, k = 3). The GAM plot showed a significant relationship between the catch and the predictor variables (SSS, SST, SSHa, Current speed and Chl-a). SSS from 32-37 ppt positively affected the expected abundance. Similarly, SST showed a positive effect from 25 to 29°C and had a negative effect on catch rate at SST above 29 °C. Positive effects on catch were recorded at SSHa values above 4 m. Current speed higher than 0.2 m/sec showed negative effects on catch rate and lower Chl-a values, which ranged between 0.00–2.14 mg m^{-3} in the study area, had a positive effect. Except for Chl-a all explanatory variables (SSS, SST, SSHa and Current speed) were found to be highly significant covariates ($p< 0.05$, $p< 0.001$, $p< 0.05$ and $p< 0.001$ respectively), in the statistical modelling of catch rate, 45.5 % of the variance was explained by the model with these variables.

Parameter	Df	F	p-value
s(SSS)	1	6.763	*p*<0.05
s(SST)	2	22.654	*P*<0.001
s(SSHa)	2	3.627	*P*<0.05
s(current)	1	15.663	*P*<0.001
s(Chl-a)	1	1.026	*P*>0.05

Table 5. Summary of parameter estimates applied to explanatory variables (*X. gladius*)

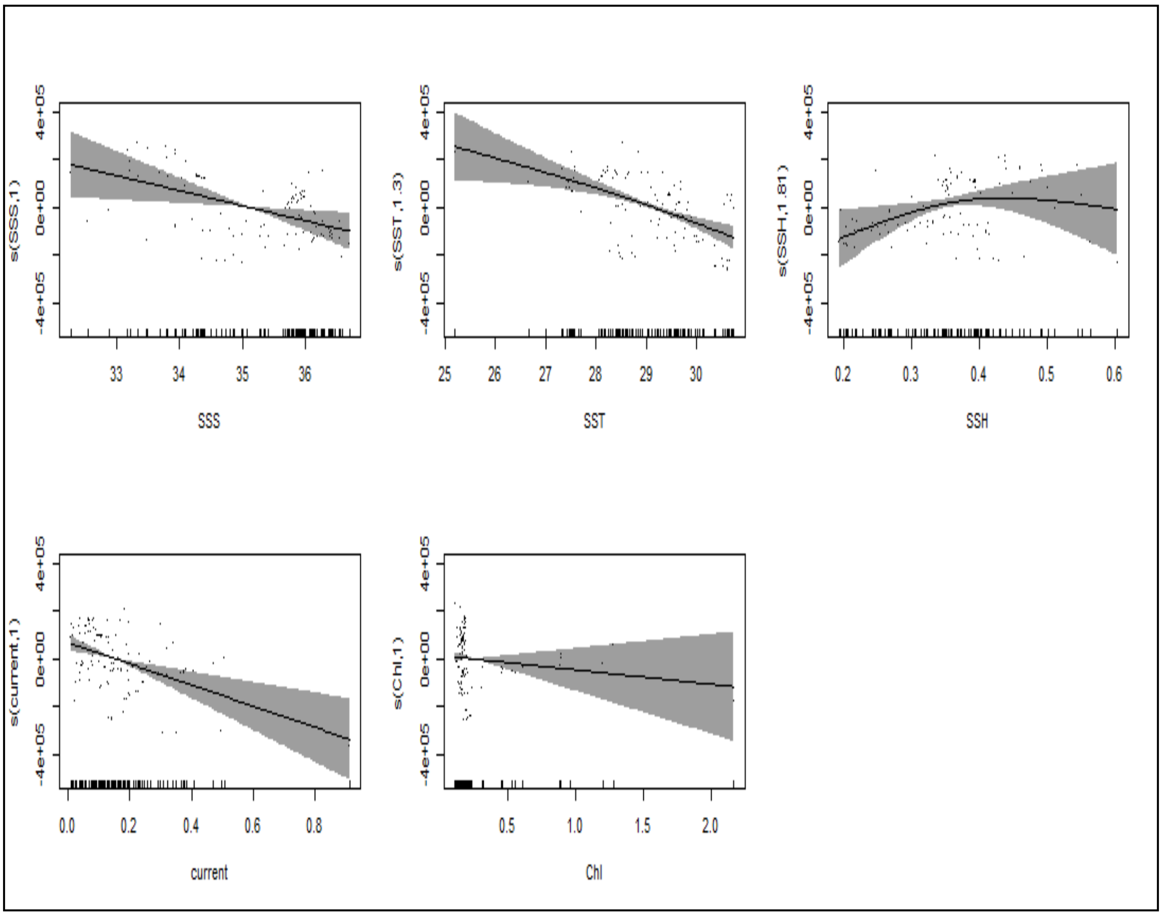

Figure 6. Response plots for environmental parameters on the density distribution of X. gladius along the Western Indian EEZ (a) SSS (b) SST (c) SSHa (d) Current speed (e) Chl-a

Length–weight relationship

The lower jaw fork length (LJFL) of swordfish sampled during 2022–2025 (n = 171) ranged from 57.7 to 294.8 cm (mean = 135.8 cm), while body weight ranged from 3.5 to 132.7 kg (mean = 22.6 kg). The length–weight relationship of swordfish was highly significant ($P < 0.001$) and was described by the equation $W = 2.27 \times 10^{-6} L^{3.131}$ ($R^2 = 0.876$), indicating that 87.6% of the variation in body weight was explained by lower jaw fork length. The estimated allometric coefficient was b = 3.131 ± 0.091 (SE). Although this point estimate was marginally above the theoretical isometric value of 3, a Student's t-test showed that the 'b' value did not differ significantly from 3 (t = 1.45, df = 169, P = 0.15), indicating isometric growth, whereby body weight increased proportionally with the cube of length. Such growth patterns are commonly observed in healthy pelagic fishes and may reflect favourable environmental conditions and food availability.

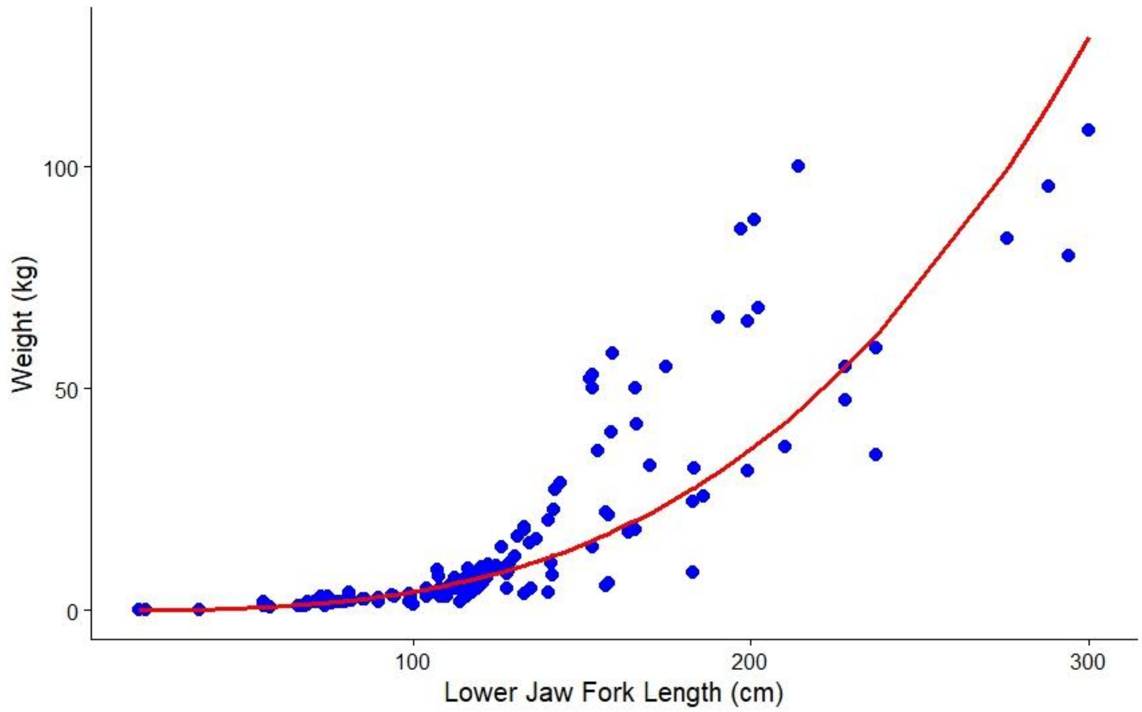

Figure 7. L-W relation of swordfish based on lower jaw fork length (LJFL, cm) and body weight (kg)

Length at First Maturity

The logistic regression model described the relationship between lower jaw fork length and the proportion of mature swordfish. The fitted model was highly significant (Intercept = −5.502 ± 0.230 SE; Length = 0.0366 ± 0.0015 SE; z = 25.20, P < 0.001), indicating that the probability of maturity increased significantly with increasing fish length. The model provided a good fit to the data, with a residual deviance of 57.36 (20 df) and an AIC of 139.45. The estimated length at first maturity (L_{50}) was 150.34 cm LJFL, indicating that 50% of the swordfish population attained sexual maturity at this length. The maturity ogive showed a gradual increase in the proportion of mature individuals from smaller size classes, followed by a rapid increase between 140 and 180 cm LJFL, with nearly all individuals attaining maturity beyond 220 cm LJFL.

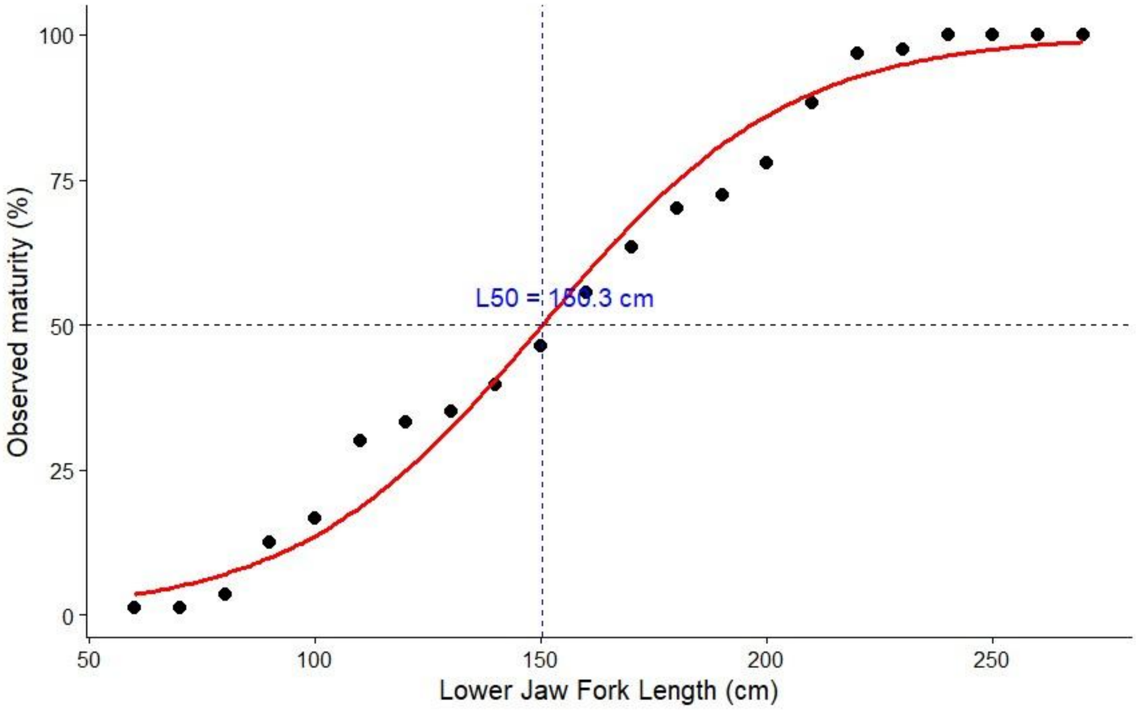

Figure 8. Logistic maturity ogive of swordfish (*Xiphias gladius*) showing the relationship between lower jaw fork length (LJFL, cm) and the observed maturity (%)

5. Conclusion

Over 2016–2025, sailfish landings along the Indian coast averaged approximately four times those of swordfish, a difference that was highly statistically significant and large in magnitude (paired $t(9) = 9.30$, $p < 0.0001$; Wilcoxon $W = 55$, $p = 0.002$; Cohen's $d = 2.94$), while the two species' annual landings were positively and significantly correlated ($r = 0.77$), consistent with substantial co-capture. Neither species showed a statistically significant linear or monotonic trend over the ten-year period (OLS $p = 0.213$ and $p = 0.699$; Mann–Kendall $p = 0.283$ and $p = 0.858$, for sailfish and swordfish respectively) despite compound annual growth of 7–8% per year and a pronounced increase in 2025, a pattern attributable to high interannual variability relative to the limited number of years available for analysis rather than to a confirmed absence of underlying change. Landings differed significantly among the six billfish species/categories examined (Kruskal–Wallis $H = 34.15$, $p < 0.0001$), with sailfish significantly exceeding blue, black, and striped marlin but not swordfish or the aggregated Marlin spp. category. Collectively, these findings support the recommendation that future management and conservation measures for India's billfish resources should explicitly account for the predominantly coastal nature of the fishery documented here and should be underpinned by continued, effort-standardised, species-resolved data collection. In addition, the Government of India has implemented a 61 days annual fishing ban on mechanised and motorised fishing boats, trawlers, purse seiners, and deep-sea fishing vessels operating in the Exclusive Economic Zone (EEZ), with the aim of protecting fishery resources during their peak breeding season. Such seasonal management measures, together with improved monitoring, effort-standardised and species-specific data collection, could contribute to the sustainable management and conservation of India's billfish resources.

References

1. Al-Kharusi, L.H. (2008) 'Predicting the distribution and abundance of emperor fishes (Lethrinus spp.) in the Arabian Sea using two-stage generalized additive models and a geographic information system', Journal of Agricultural and Marine Sciences, 13(1), pp. 7–22.

2. Anil, M. K. (2021). Status of billfish fishery along the Indian coast. Marine Fisheries Information Service, Technical & Extension Series, No. 250, 21–24. ICAR-Central Marine Fisheries Research Institute, Kochi.

3. Block, B. A., Jonsen, I. D., Jorgensen, S. J., Winship, A. J., Shaffer, S. A., Bograd, S. J., Hazen, E. L., Foley, D. G., Breed, G. A., Harrison, A.-L., Ganong, J. E., Swithenbank, A., Castleton, M., Dewar, H., Mate, B. R., Shillinger, G. L., Schaefer, K. M., Benson, S. R., Weise, M. J., Henry, R. W., & Costa, D. P. (2011). Tracking apex marine predator movements in a dynamic ocean. Nature, 475(7354), 86–90.

4. Brodie, S., Hobday, A.J., Smith, J.A., Everett, J.D., Taylor, M.D. and Gray, C.A. (2015) 'Modelling the oceanic habitats of two pelagic species using recreational fisheries data', Fisheries Oceanography, 24(5), pp. 463–477.

5. Collette, B. B., Di Natale, A., Fox, W., Graves, J., Juan Jorda, M., Pohlot, B., Restrepo, V., & Schratwieser, J. (2022). *Istiophorus platypterus*. The IUCN Red List of Threatened Species 2022: e.T170338A46649664.

6. Government of India. (2016–2025). National Report of India (annual submissions, 2016–2025). Report to the Scientific Committee, Indian Ocean Tuna Commission (IOTC), Victoria, Seychelles.

7. Hastie, T. J., & Tibshirani, R. J. (1990). Generalized Additive Models. Monographs on Statistics and Applied Probability. Chapman and Hall, London.

8. Kendall, M. G. (1975). Rank Correlation Methods (4th ed.). Charles Griffin, London.

9. Mann, H. B. (1945). Nonparametric tests against trend. Econometrica, 13(3), 245–259.

10. Nakamura, I. (1985). FAO species catalogue. Vol. 5. Billfishes of the world: An annotated and illustrated catalogue of marlins, sailfishes, spearfishes and swordfishes known to date. FAO Fisheries Synopsis No. 125, Vol. 5. Food and Agriculture Organization of the United Nations.

11. Pons, M., Branch, T. A., Melnychuk, M. C., Jensen, O. P., Brodziak, J., Fromentin, J. M., Harley, S. J., Haynie, A. C., Kell, L. T., Maunder, M. N., Parma, A. M., Restrepo, V. R., Sharma, R., Ahrens, R., & Hilborn, R. (2017). Effects of biological, economic and management factors on tuna and billfish stock status. Fish and Fisheries, 18(1), 1–21.

12. Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association, 63(324), 1379–1389.

13. Sharma, R., Pons, M., Martin, S., Kell, L., Walter, J., Lauretta, M., & Schirripa, M. (2018). Factors related to the decline and rebuilding of billfish stocks in the Atlantic and Indian oceans. ICES Journal of Marine Science, 75(2), 880–891.

14. Shimose, T., Yokawa, K., & Saito, H. (2010). Habitat and food partitioning of billfishes (Xiphioidei). Journal of Fish Biology, 76(10), 2418–2433.

15. Smith, L. M., Williams, S. M., Ferrette, B. L. S., Holmes, B. J., Kadagi, N. I., Lu, C.-P., Ortega-Garcia, S., Pepperell, J. G., Tibbetts, I. R., Wambiji, N., Wambua, S., & Dudgeon, C. L. (2025). Global analyses of sailfish (*Istiophorus platypterus*) using next-generation sequencing reveal multiple populations. ICES Journal of Marine Science, 82(12), fsaf232.

16. Solanki, H.U., Bhatpuria, D. and Chauhan, P. (2016) 'Applications of generalized additive model (GAM) to satellite-derived variables and fishery data for prediction of fishery resources distributions in the Arabian Sea', Geocarto International, 32(1), pp. 30–43.

17. Su, N. J., Sun, C. L., Punt, A. E., Yeh, S. Z. and DiNardo, G., (2011). Modelling the impacts of environmental variation on the distribution of blue marlin, *Makaira nigricans*, in the Pacific Ocean. ICES J. Mar. Sci., 68: 1072-1080.

18. Surya, S., Prathibha, R., Abdussamad, E.M., Asha, T.L., Santhosh, B., Nayak, B.B., Karankumar, R., Mini, K.G., Kingsly, J.H. and Anil, M.K. (2022) 'Habitat suitability of Indo-Pacific sailfish *Istiophorus platypterus* (Shaw, 1792) in the Arabian Sea', Indian Journal of Fisheries, 69(2), pp. 19–29.

Abstract

Billfishes support economically important artisanal, commercial, and recreational fisheries along the Indian coast, yet long-term assessments of their landings remain limited. This study analysed ten years (2016–2025) of landing statistics to evaluate temporal trends and species composition of Indian billfish fisheries. Sailfish (Istiophorus platypterus) dominated the landings, averaging 7,932 ± 794 t $year^{-1}$, followed by swordfish (Xiphias gladius) with 2,079 ± 239 t $year^{-1}$, and sailfish landings were significantly higher than swordfish throughout the study period (paired t-test, $p < 0.0001$). No significant long-term temporal trend was detected for either species despite marked interannual variability. Generalized Additive Model analysis showed that sea surface salinity (SSS), sea surface temperature (SST), sea surface height anomaly (SSHa), and current speed significantly influenced swordfish catch rates ($p < 0.05$), whereas chlorophyll-a was not significant, and the model explained 45.5% of the variation in catch rates. Swordfish exhibited higher habitat suitability in waters with SST of 25–29°C, salinity of 32–37 ppt, positive SSHa (>4 m), and current speeds below 0.2 m s^{-1}, providing valuable information for habitat prediction, fisheries management, and sustainable exploitation of billfish resources in Indian waters. The lower jaw fork length (LJFL) of swordfish analysed between 2022-2025 ranged from 57.7 to 294.8 cm, with a mean of 135.8 cm, while body weight varied from 3.5 to 132.7 kg (mean: 22.6 kg). The length–weight relationship of swordfish was highly significant (R^2 = 0.876, $P < 0.001$) and was described by the equation $W = 2.27 \times 10^{-6} L^{3.131}$, with the allometric coefficient (b = 3.131) not differing significantly from the theoretical isometric value of 3 (P = 0.15), indicating isometric growth.

Keywords: billfish; sailfish; swordfish; landings trend; India; EEZ