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A flotsam-associated fishery in the Indian Ocean, and its potential impact on pelagic bycatch species

*N.B. Prasada Punyadeva[1], K.H.M. Ashoka Deepananda[2], Nuwan D.P. Gunawardane[3], Dayananda S. Digamadulla[4], Upali S. Amarasinghe[5]**

[1]National Aquatic Resources Research and Development Agency, Crow Island, Colombo 15, Sri Lanka
[2]Department of Fisheries and Aquaculture, Faculty of Fisheries and Marine Science & Technology, University of Ruhuna, Matara 80000, Sri Lanka
[3]Department of Fisheries and Aquatic Resources, New Secretariat, Maligawatte, Colombo, Sri Lanka
[4]Department of Aquaculture and Fisheries, Wayamba University of Sri Lanka, Makandura, Gonawila 60170, Sri Lanka
[5]Department of Zoology and Environmental Management, University of Kelaniya, Kelaniya 11600, Sri Lanka

*Corresponding author: zoousa@kln.ac.lk

https://orcid.org/0000-0002-0465-6950

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Abstract: In the deep-sea fishing boats operated from the fishery harbours of southern Sri Lanka, in addition to gillnets and longlines, encircling nets are taken onboard to operate whenever the fishing boat encounters a floating object (flotsam) in the high seas. These flotsam-associated fisheries target shade-loving fish species such as *Decapterus russelli* (Rüppell) and *Elagatis bipinnulata* (Quoy & Gaimard), while juvenile tuna species are also caught as bycatch. The present study was an attempt to investigate the status of the fisheries of *D. russelli* and *E bipinnulata* using length-based stock assessment and to elucidate the impact of these fishing strategies on three species of small tuna and three species of large tuna. The analysis revealed that *D. russelli* stock was optimally exploited, while *E. bipinnulata* showed sub-optimal exploitation, indicating that both stocks remain at safe levels. Length-based indicators (LBIs) showed that the proportion of fish exceeding the mean length at first capture was very low or zero for both small and large pelagic tuna species, while the proportion of immature individuals in the landings was high, suggesting potential adverse impacts of ring netting on these stocks. Although there are claims that catching juvenile tuna around floating objects does not necessarily lead to overfishing, the impact of ring netting on large pelagic tuna fish stocks in the Indian Ocean is a matter of concern, particularly given the substantial increase in ring net effort reported in this study. Therefore, the expansion of this fishery underscores the urgent need for regulatory measures to prevent the risk of future overfishing of tuna stocks.

Keywords: Drifting objects, FADs, Length-based indicators, pelagic fish, tropical tuna

INTRODUCTION

In the world's oceans, natural and artificial floating objects are widespread, and fishing activities are often focused around them due to the well-established association of many pelagic fish species with these structures (Dupaix et al. 2024). However, fisheries associated with artificial floating objects, popularly known as fish aggregation devices (FADs), deployed in many regions for enhancement of pelagic fisheries, are often criticized for their potential negative impacts on tuna stocks, for high levels of bycatch and threats to the biodiversity of tropical pelagic ecosystems (Dagorn et al. 2012;

Henich et al. 2019; Tidd et al. 2023). In the Indian Ocean, apart from the artificial floating objects (i.e., FADs) (Amandè et al. 2008; Noranarttragoon et al. 2013; Mitsunaga et al. 2013), fisheries associated with natural floating objects such as driftwood and debris from human activities, such as marine cargo, are reported (Ariyarathne and Amarasinghe 2012; Chathurika and Dissanayake 2016; Dumont et al. 2024). Most of the multi-day fishing vessels (i.e., those are engaged in fishing in the sea for more than one-day), operating from the fishery harbours on the south-western and southern coasts, occasionally carry surrounding nets, along with drift gillnets and tuna longlines. In Sri Lanka, these surrounding nets are called ring nets, although they do not exactly conform to the definition of the Food and Agriculture Organisation (FAO 2022b) (i.e., a hybrid form between a purse seine and a lampara net). In the present study, therefore, the term 'ring net' is used to describe flotsam-associated surrounding nets.

Species caught in ring nets associated with flotsam in the Indian Ocean off Sri Lanka consist of common species such as *Decapterus russelli* (Rüppell), *Elegatis bipinnulata* (Quoy & Gaimard), *Canthidermis maculatus* (Bloch), *Coryphaena hippurus* Linnaeus, etc. (Ariyarathne and Amarasinghe 2012; Chathurika and Dissanayake 2016). Of these, *Decapterus russelli*, *Elegatis bipinnulata* are the most abundant and, as such, they can be considered as target species in the ring net fishery. Also, several other species are caught, which can be considered as non-target species or bycatch species, including tuna and tuna-like species. As in purse seiners associated with FADs, the searching efficiency of fishers has dramatically improved in the ring net fisheries associated with flotsam, and this might be a significant driver for the rapid expansion of ring net fisheries, especially off the southwest coast of Sri Lanka.

As observed in many fisheries associated with FADs across the Indian Ocean (Noranarttragoon et al., 2013) and elsewhere (Dupaix et al. 2024), juvenile tunas are exclusively caught in ring net catches off Sri Lanka (Ariyarathne and Amarasinghe 2012; Chathurika and Dissanayake 2016). It is therefore essential to investigate the potential impact of ring net fisheries on non-target tuna species to develop effective management strategies for the fishery. This is particularly crucial, as Dumont et al. (2024) stated, because even when the proportion of bycatch is relatively low, the large scale of these fisheries can still exert significant impacts on pelagic ecosystems. As length frequency data are often the simplest information that can provide useful indicators of the exploitation of a given population, the selectivity of the fishery and/or the proportion of mature individuals in catches, and trends in a fishery can be investigated by length-based indicators (LBIs) (Cope and Punt 2009; Ahrens et al. 2020). This is especially due to the reason that one of the primary factors influencing changes in the length structure of a population is fishing pressure, which often drives the mean length and overall length composition of a fishery toward smaller sizes as fishing intensity increases (Ault et al. 2019). As pointed out by Capello et al. (2023), science-based approaches need to be adopted for the management of ring net fishery associated with flotsam. In the present study, an attempt was made to investigate population dynamics of two dominant target species in the ring net fishery, *D. russelli* and *E. bipinnulata*, using length-based stock assessment methods, and to evaluate the status of the fisheries exploitation on the non-target tuna species using LBIs.

MATERIALS AND METHODS

Ethical approval

As no live animals were used in this study, ethical approval from the institutional ethics review committee was not required.

The fishery

The multi-day fishing boats operated from the fishery harbours of Sri Lanka are locally known as inboard multi-day boats (hereafter IMULs), having a size range of 9–17 m in length. In each IMUL, there are 3–10 fishers as crew members, depending on the size of the boat. The IMULs generally target pelagic tuna and tuna-like species using drift gillnets and/or longlines. For a fishing trip on an IMUL, the duration varies from 5 to 30 days, depending on the limited deck space and ice-holding capacity, as well as the manual operation of fishing gear (Gunawardena et al. 2021). During the last three decades or so, there has been a recent trend in the multi-day fishing operations, especially among the IMULs operated from the fishery harbours on the southwestern and southern coasts of Sri Lanka, targeting fish species associated with floating objects (i.e., flotsam-associated fish) using surrounding nets (Ariyarathna and Amarasinghe 2012). The dimensions, including structure and filament characteristics, are given by Ariyarathna and Amarasinghe (2012), and some characteristics are also given in Table 1. Although the main target species are Indian scad (*Decapterus macarellus*, *D. macrosoma* and *D. russelli*) and rainbow runner (*Elegatis bipinnulata*), juveniles of several other pelagic species are also caught as bycatch in this fishery (Ariyarathna and Amarasinghe 2012). It has been reported that in the Indian Ocean, there has been a dramatic increase in IMULs of flotsam-associated ring net fishing (200% increase) from 2,805 boats in 2021 to 8,416 in 2024 (DFAR 2025).

Ring net fishing operation

When an IMUL encounters a floating object such as a dead tree, a crew member conducts underwater observations using a pair of goggles, and when enough fish aggregate beneath the floating object, the skipper decides to encircle the floating object using a surrounding net. The fish caught are removed with a large scoop net. When the boat's storage capacity is full, the skipper invites another boat operating in the area to harvest the remaining catch. The second boat, however, has to pay the first boat 33% or 50% of the income derived from the remaining catch. For each IMUL, the net profit from the landings is shared by the boat owner, skipper and crew members according to a mutually agreed-upon procedure. Generally, the profit-sharing formula is that 50% of the net income goes to the boat owner and 50% to the crew members (Ariyarathna and Amarasinghe 2012).

Table 1. Dimensions, structure and filament characteristics of ring nets used in the multiday boats operated from Sri Lankan fishery harbours.

Attribute	Values
Length (range)	185 – 498 m
Height (range)	28 – 74 m
Head rope	8 mm Ø nylon
Lead line	8 mm Ø kuralon
Number of buoys attached to the head rope using a separate nylon rope	120 - 130
Interval of floats in the head rope	50 cm
Interval of floats in the bund area	20 – 25 cm
Cylindrical lead weights attached to the lead rope§	20 mm Ø and 60 mm length (attached to the middle area of the rope, about 50 m from either end of the net, at intervals of 4 m)
Thickness of net bridle	12 mm Ø kuralon
Purse rings	100 mm Ø brass, and each weight ranges from 300 to 900 g
Mesh size (bunt)*	2.5 cm
Mesh size (body)**	3.7 cm
Twine thickness	18 - 21 ply (bunt) 9 ply (body)

§ Two cement sinkers of about 2.5 to 3 kg are also attached to each end of the net.
* The "bunt" is the section of the net where the catch is typically gathered.
** The “body” refers to the central part of the net, which is the vertical wall of netting used to surround a school of fish.

Data collection

The present analysis was conducted from March 2018 to May 2021. The landings of 1,109 multiday boats at four fishery harbours along the South-Western and Southern coasts of Sri Lanka (i.e., Beruwala, Galle, Gandara, Tangalle; Figure 1) were examined to collect monthly length frequency data of dominant species. Most of these fishing vessels were engaged in ring net fishing (Figure 1), targeting 'shade-loving' fish species such as Indian scad (*Decapterus macarellus*, *D. macrosoma* and *D. russelli*) and rainbow runner (*Elegatis bipinnulata*). Of the three species of *Decapterus*, however, *D. russelli* formed over 98% of the landings. Also, the contribution of various other species, by weight, to the landings of the ring net fishery, which were treated as 'bycatch', was recorded from the logbook data of each boat observed. As ring netting is an opportunistic fishing method to operate only when the IMULs encounter a floating object, some boats were noted to use a combination of fishing gear (i.e., ring nets plus longlines and ring nets plus drift gillnets; Figure 1). Skippers of the multi-day boats engaged in ring netting and a combination of other fishing gear, together with ring nets, were interviewed to document fishing locations as reported in the logbook records. For the collection of length frequency data (LFD) of main target species, i.e., *D. russelli* and *E. bipinnulata*, IMULs engaged in a combination of fishing gear were avoided as the size distributions of such boats may have been affected by the fishing gear (hook and gillnet) selection. Accordingly, length frequency data of target species and 'bycatch' species were collected monthly only from the landings of ring net fisheries in the four fishery harbours during the study period of 2018-2021. Fork lengths of randomly selected specimens of each species were measured to the nearest 1 cm below their actual length. It must be noted, however, that ideally, a length-based stock assessment protocol for multi-species and multi-gear fisheries, such as in the present study, should have included all dominant species across all major fisheries for comparative analysis. Within the scope of this study, however, the analysis was restricted to LFD of species caught in ring net fisheries.

Data analysis

For length-frequency data analysis, size ranges with maximum lengths close to the recorded asymptotic lengths in www.fishbase.org (Froese and Pauly 2024) were available only for *Decapterus russelli* and *Elegatic bipinnulata*, two of the main target species in the ring net fishery. Monthly length frequency data (fork length in cm) collected from January 2018 to June 2020 and grouped into 2 cm length classes were analysed using FiSAT II (Gayanilo et al. 1996) and TropFishR (Mildenberger et al. 2017) software. Although improved algorithms are available in TropFish R, in the present analysis, FiSAT II package was also employed due to the availability of the analytical approach for correcting LFD for the effect of gear selection on smaller size classes as described by Pauly (1986). The stepwise procedures of estimating von Bertalanffy growth parameters [i.e., asymptotic fork length (FL_∞) and growth constant (K)] described by Athukorala and Amarasinghe (2010) and Amarasinghe et al. (2017), together with algorithms of TropFishR (Mildenberger et al. 2017) were used in the present analysis. Here, the von Bertalanffy growth model is of the form,

$$FL_t = FL_\infty (1 - \exp(-K(t - t_o))) \quad (1)$$

where FL_t is the fork length in cm at age t, FL_∞ is the asymptotic fork length in cm, K is the growth constant, and t_o is the theoretical age when length is zero.

The remaining analyses, which included determining mortality rates, lengths at first capture, recruitment patterns, and relative yields per recruit, were performed using FiSAT II software. Total mortality (Z) was determined from the length-converted catch curve, and natural mortality (M) from Pauly's (1980) empirical equation. As the empirical relationship of Pauly (1980) was derived from the asymptotic total length (TL_∞), the estimated asymptotic fork length (FL_∞) values of fish species were converted to TL_∞ using their TL-FL relationships as reported in www.fishbase.org. The fishing mortality (F) and exploitation ratio (E = F/Z) of the two species were also determined. Through a detailed analysis of the ascending part of the length-converted catch curve, a plot of probabilities of capture against FL was obtained, and the length at 50% of probability of capture was considered as the mean fork length at first capture (FL_{50}).

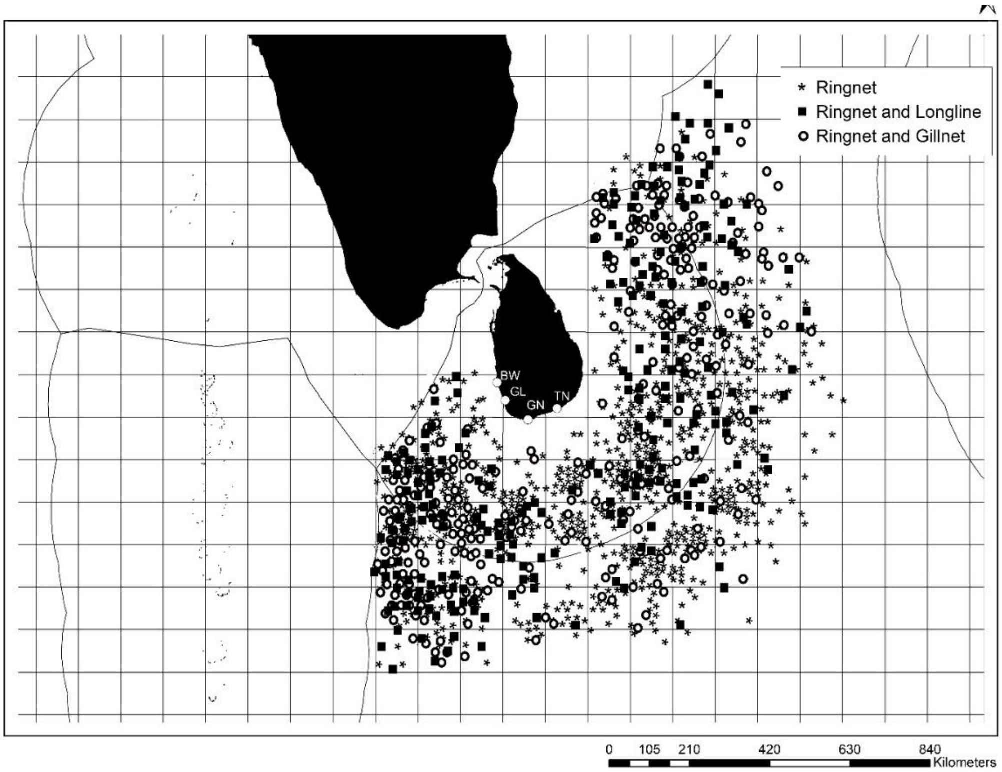

Fig 1. Map of ring net fishing locations of Sri Lankan IMULs in the Indian Ocean and four fishery harbours of Sri Lanka (BW: Beruwala; GL: Galle; GN: Gandara; TN: Tangalle) where sampling was carried out.

The recruitment patterns of *D. russelli* and *E. bipinnulata*, as implemented in FiSAT II software, were determined, and the relative yield-per-recruit (Y'/R) analyses were performed incorporating probabilities of capture (Pauly and Soriano 1986). The exploitation ratio (E) considering the level which keeps 50% of the unexploited stock biomass ($E_{0.5}$) and the optimal level (E_{opt}) where maximum Y'/R could be achieved, and $E_{0.1}$, i.e., the E value corresponding to 10 % of maximum rate of increase of Y'/R as reference points, optimal fishing strategies for the two target species in the ring net fishery were determined.

Apart from these analyses, attempts were made to evaluate the status of exploitation of pelagic fish species using length-based indications (LBIs) as proposed by Froese (2004). The Froese (2004) provided management reference points as P_{mat} ('Let them spawn', i.e., the proportion of mature fish in the catch), P_{opt} ('Let them grow', i.e., percentage of fish caught at optimum length), and P_{mega} ('Let the mega spawners live', i.e., percentage of old, large fish in the catch), defined as follows:

$$P_{mat} = \sum_{L_{mat}}^{L_{max}} P_L \quad (2)$$

$$P_{opt} = \sum_{0.9\,L_{opt}}^{1.1\,L_{opt}} P_L \quad (3)$$

and

$$P_{mega} = \sum_{1.1\,L_{opt}}^{L_{max}} P_L \quad (4)$$

where P_L is the proportion of the catch that is in length class L, L_{mat} is the length at 50% maturity, L_{max} is the maximum length (which L_∞ was taken in the present analysis), and L_{opt} is the length at 50% selection or mean length at first capture.

In addition, to assess the impact of fishing on non-target pelagic species, a measure to quantify the proportion of immature fish (P_{imm}), which is believed to represent the degree of growth overfishing, the following LBI was also determined.

$$P_{imm} = \sum_{L_{min}}^{L_{mat}} P_L \quad (5)$$

where L_{min} is the minimum length in the catch sample.

For the bycatch species, whose length frequency data (LFD) were not sufficient to evaluate stock status using length-based stock assessment for six species, namely, *Auxis rochei* (Risso), *A. thezard* (Lacepède), *Euthynnus affinis* (Cantor), *Katsuwonus pelamis* (Linnaeus), *Thunnus albacares* (Bonnaterre), and *T. obesus* (Lowe), the above LBIs were used for assessment of stock status. For this purpose, the following empirical relationships (Froese and Binohlan, 2000) were used.

$\log_{10}L_{\infty} = 0.044 + 0.9841 * \log_{10}(L_{max})$ (6)
$\text{Log}_{10}L_{m} = 0.8979 * \log_{10}(L_{\infty}) - 0.0782$ (7)
$\log_{10}L_{opt} = 1.0421 * \log_{10}(L_{\infty}) - 0.2742$ (8)
$\log_{10}L_{opt} = 1.053 * \log_{10}(L_{m}) - 0.0565$ (9)

Here, L_{max} values of the six pelagic fish species considered were obtained from www.fishbase.org reported for the stocks in the Indian Ocean.

It should be noted, however, that using these empirical equations for bycatch species is a pragmatic solution for data-limited species; thus, the results represent theoretical predictions rather than values empirically derived from Sri Lankan stocks. The validity of these general equations for specific Indian Ocean populations is therefore uncertain.

RESULTS

Although ring netting in IMULs is an opportunistic fishing strategy that is performed only when a boat encounters a floating object, as can be seen from Figure 1, fishing operations of IMULs engaged in ring netting and combination with longlining and drift gillnetting were mostly restricted to the EEZ of Sri Lanka. Although ring net fishing targeted a handful of species which are attracted to shade under the flotsam, such as *D. russelli* and *E. bipinnulata*, several other pelagic fish species (apart from skates, which were generally considered demersal) were caught as bycatch (Table 2). From the size ranges of fish species caught, it is evident that many bycatch species of this fishery were juvenile stages.

Table 2. Sample size ranges of length frequency data collected and percentage contribution of different fish species (by weight).

Species	Sample size (range)	Length range (FL in cm)	%
Decapterus russelli	750 - 2228	13 - 32	39.0
Elegatis bipinnulata	450 - 3150	17 - 72	7.0
Auxis thezard	700 - 2950	16 - 35	8.7
Auxis rochei	550 - 2600	16 - 32	4.8
Euthynnus affinis	600 - 2800	20 - 37	5.2
Katsuwonus pelamis	400 - 2950	20 - 42	18.3
Thunnus albacares	400 - 1850	20 - 38	3.2
Thunnus obesus	50 - 1850	20 - 35	3.0
Others*	-	-	10.8

* *Canthidermis maculatus*, *Coryphaena hippurus*, *Istiophorus platypterus*, *Xiphias gladius*, Carangids, Seer fish, Sharks, Skates

The von Bertalanffy growth curves, superimposed on the original LFD and restructured LFD of *D. russelli* and *E. bipinnulata* are shown in Figure 2. Accordingly, von Bertalanffy growth models were as follows:

For *D. russelli*: $FL_t = 33.7\,(1 - \exp(-0.70(t - t_o)))$
For *E. bipinnulata*: $FL_t = 75.8\,(1 - \exp(-0.38(t - t_o)))$

The growth performance indices (φ') of both species (Table 3) agreed with those reported in www.fishbase.org, and as such, estimated growth parameters were biologically reasonable.

Total mortality rates (Z) estimated by means of length-converted catch curves (Figure 3), natural mortality (M), fishing mortality (F) and exploitation ratio (E) of *D. russelli* and *E. bipinnulata* are given in Table 3. Here, three reference points, namely E value corresponding to 50% of spawning biomass ($E_{0.5}$), the value corresponding to optimal relative yield-per-recruit (E_{opt}) and the E value which corresponds to 10% of the maximum rate of Y'/R increase with increasing E ($E_{0.1}$), were considered in comparison with the current exploitation ratio ($E_{curr.}$). As mentioned above for the estimation of M using Pauly's (1980) function, asymptotic fork length (FL_∞) values of fish species converted to TL_∞ using their TL-FL relationships (Appendix I) were used, and the mean habitat temperature was taken as 27°C. The fork lengths at 50% retention (FL_{50} or FL_c) of *D. russelli* and *E. bipinnulata*, determined from the plots of probabilities of capture against FL (Figure 4) and those estimated from the equation (8) above, are also incorporated in Table 3. The recruitment patterns of both *D. russelli* and *E. bipinnulata* (Figure 5) were bimodal. Results of the relative yield-per-recruit analyses incorporating probabilities of capture (Figure 6) indicated that both the E_{opt} and $E_{0.1}$ were greater than the level which would keep 50% of the unexploited stock biomass or spawning biomass ($E_{0.5}$) (Hoggarth et al. 2006). Also, the current exploitation ratios ($E_{curr.}$) of *D. russelli* and *E. bipinnulata* were 0.42 and 0.25, respectively, suggesting that, as they were close to $E_{0.5}$, further attempts should not be made to optimize Y'/R considering the reference points of E_{opt} and $E_{0.1}$, although the current exploitation ratio ($E_{curr.}$) of *E. bipinnulata* (0.25) was much lower than the E_{opt} (0.70) or $E_{0.1}$ (0.57) (Table 3). The summary of the results of the estimated reference points of optimal exploitation of *D. russelli* and *E. bipinnulata* stocks is also given in Table 3.

The length-based indicators (LBIs) to evaluate the status of exploitation of target and non-target pelagic fish species in the ring net fishery are given in Table 4. The LBIs, determined from the length frequency data of the landings of two target species of the ring net fisheries (Figure 7), indicate that the proportion of immature individuals of *D. russelli* (P_{imm}) is the lowest while higher values of P_{mat}, P_{opt} and P_{mega} indicate that the stock is in a relatively healthy status in terms of current level of fisheries exploitation (Figure 7a(ii)). As evident from the Y'/R analysis, further increase of E beyond the current level might lead to a significant decrease in the spawning biomass (Figure 6a). In *E. bipinnulata* however, although a wide range of length classes was present (Figure 7b(i)), the proportion of immature counterparts in the landings (P_{imm}) was relatively higher (Figure 7b(ii)). As the exploitation ratio (E) of this species in the ring net fishery was relatively low (0.25; Table 3), and given the comparatively lower values of P_{mat}, P_{opt} and P_{mega} for *E. bipinnulata* (Figure 7b(ii)), there appears to be potential for further increase of fishing on this species subject to increase of L_c to minimize growth overfishing.

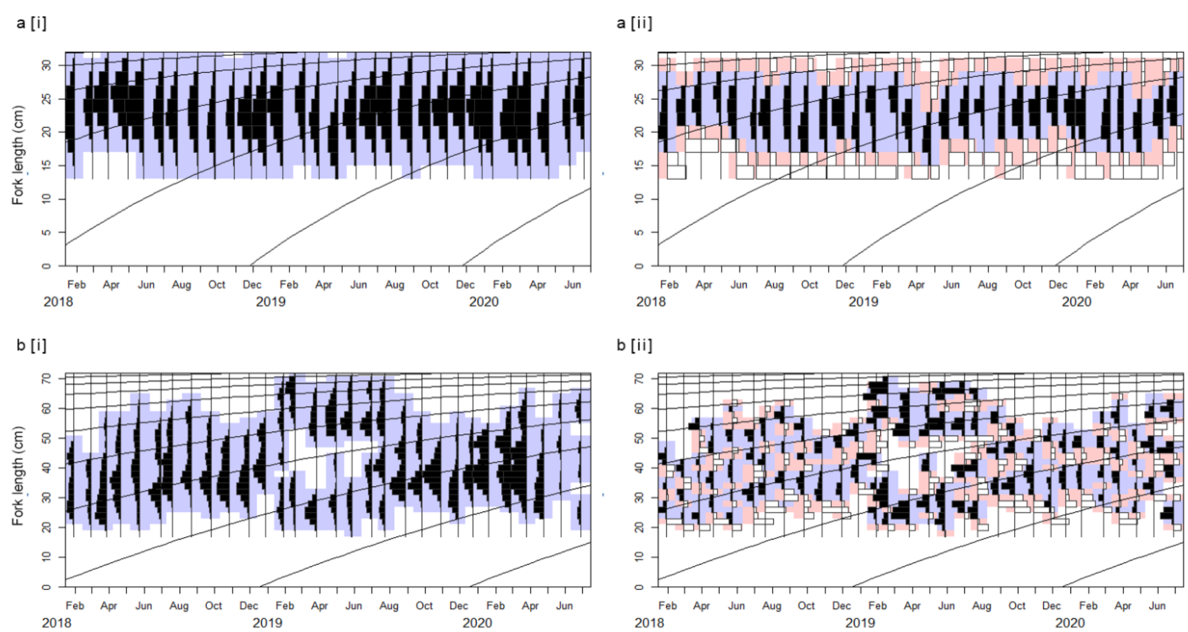

Fig 2. von Bertalanffy growth curves of (a) *Decapterus russelli* and (b) *Elegatis bipinnulata* superimposed on [i] original length frequency data and [ii] restructured data

Table 3. Growth and mortality parameters of *D. russelli* and *E. bipinnulata*.

Parameter (Symbol)	Unit	*D. russelli*	*E. bipinnulata*
Asymptotic fork length (FL_∞)	cm	33.7	75.7
Growth constant (K)	$year^{-1}$	0.7	0.38
Growth performance index (φ')†	-	2.90	3.34
Total mortality (Z)	$year^{-1}$	2.27	0.92
Natural mortality (M)§	$year^{-1}$	1.31	0.69
Fishing mortality (F)	$year^{-1}$	0.96	0.23
Current exploitation ratio ($E_{curr.}$)	-	0.42	0.25
Exploitation ratio corresponding to 50 % of spawning biomass ($E_{0.5}$)	-	0.36	0.35
Optimal exploitation ratio at the maximum relative yield-per-recruit (Y'/R; E_{opt})	-	0.75	0.70
Exploitation ratio corresponding to 10 % of maximum rate of increase of Y'/R ($E_{0.1}$)	-	0.60	0.57
Fork length at 50 % retention (FL_{50})	cm	21.8	29.3

† Estimated using FL_∞. The mean φ' values reported in www.fishbase.org based on FL_∞ were 2.70 for *D. russelli* and 3.49 for E. *bipinnulata*

§ estimated from the empirical equation of Pauly (1980) using TL_∞ in cm (see Appendix I).

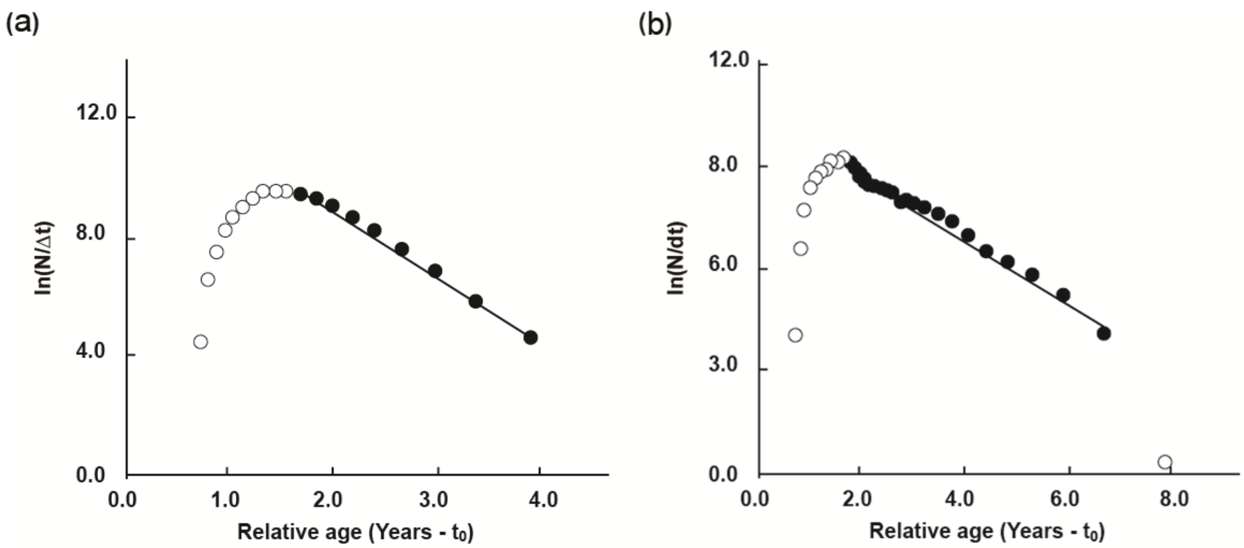

Fig 3. Length-converted catch curves of (a) *D. russelli* and (b) *E. bipinnulata*.

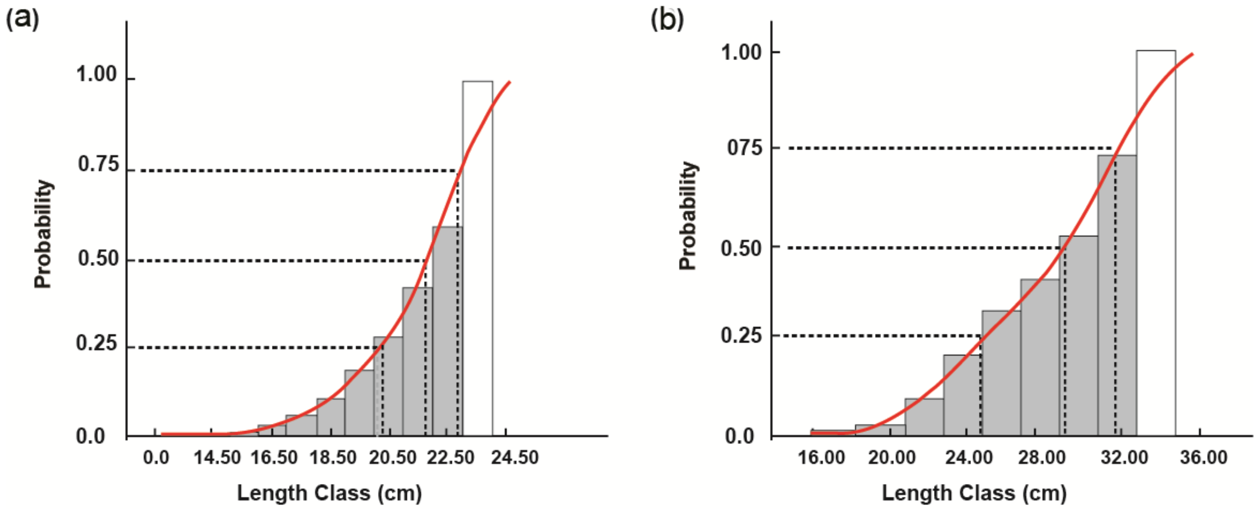

Fig 4. Probabilities of capture against fork length classes of (a) *D. russelli* and (b) *E. bipinnulata*.

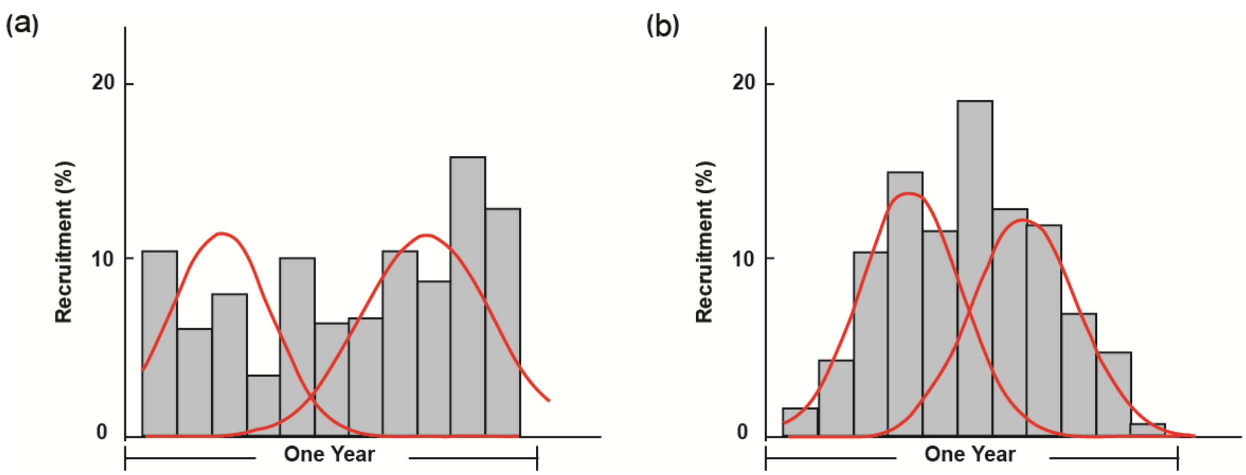

Fig 5. Recruitment patters of (a) *D. russelli* and (b) *E. bipinnulata*.

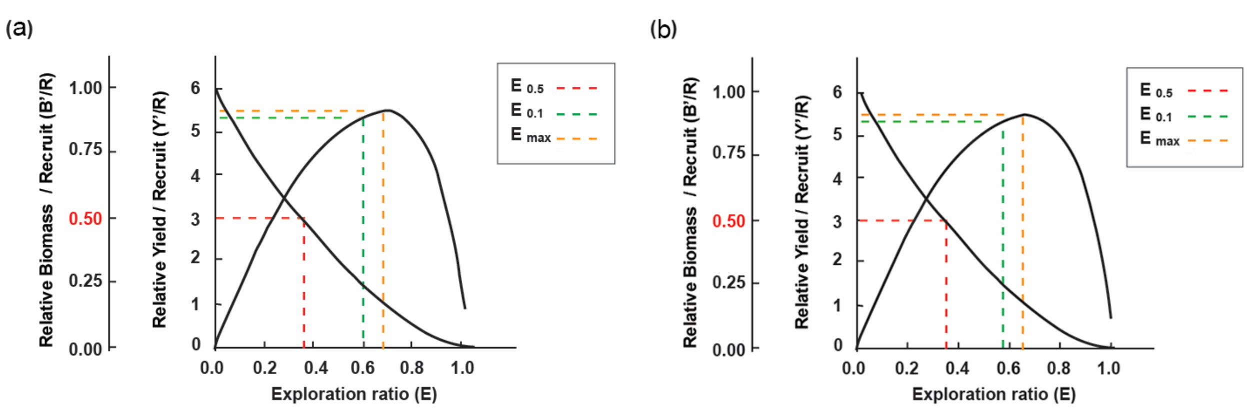

Fig 6. Relative yield-per-recruit and biomass-per-recruit of (a) *D. russelli* and (b) *E. bipinnulata*. $E_{0.5}$ - E value corresponding to 50% of spawning biomass; $E_{0.1}$ - E value corresponding to 10% of the maximum rate of Y'/R increase with increasing E; E_{max} - Optimal E producing the maximum relative yield-per-recruit.

Table 4. Reference lengths for determining LBIs of target species and bycatch pelagic species in the ring net fishery

Species	FL_{∞} (cm)	FL_{min} (cm)	FL_m (cm)§	FL_c (cm)† ($0.9\ FL_c$ – $1.1\ FL_c$)
Target species				
Decapterus russelli	33.7‡	13.5	20.2	21.8‡ (19.6 – 24.0)
Elegatis bipinnulata	75.7‡	17.5	41.7	48.3† (43.5 – 53.1)
Bycatch species (small tuna)				
Auxis thezard	51.0‡	16.5	29.3	32.0† (28.8 – 35.2)
Auxis rochei	42.5‡	16.5	24.9	26.5† (23.9 – 29.2)
Euthynnus affinis	78.9*	20.5	43.2	50.4† (45.4 – 55.4)
Bycatch species (large tuna)				
Katsuwonus pelamis	82.7*	20.5	45.1	53.0† (47.7 – 58.3)
Thunnus albacares	181.9*	20.5	91.3	120.4† (108.1 -132.4)
Thunnus obesus	205.5*	20.5	101.8	136.8† (123.1 – 150.5)

‡ Estimated from FiSAT II and TropFishR
* Estimated from Equation 6
§ Estimated from Equation 7
† Estimated from Equations 8 and 9

In the bycatch, three species of small tuna (*A. thezard*, *A. rochie* and *E. affinis*), which were caught in noticeable proportions (Table 2), were all smaller than 37 cm FL (Figure 8). The proportions of immature individuals depicted as P_{imm} were much higher in the landings, having 100% immaturity in *E. affinis* (Figures 8a(ii), 8b(ii) and 8c(ii)). Low LbIs (P_{mega}) of *A. thezard* and *A. rochie*, having high P_{imm} and zero P_{mega} of *E. affinis,* indicate that these stocks are over-exploited. Also, the occurrence of immature *E. affinis* in the landings is a clear indication of growth overfishing in this stock.

Three large tuna species (*K. pelamis*, *T. albacares* and *T. obesus*) caught as bycatch in the ring net fishery were immature (Figure 9), and all LBIs were zero indicating that further intensification of the ring net fishery is detrimental to these pelagic stocks. This is particularly significant because the contribution of *K. pelamis* in the landings of ring net fisheries is over 18% (Table 2).

DISCUSSION

Aggregation of pelagic fish species around natural floating objects is considered a form of an 'associative behaviour' of pelagic species in which fish make use of natural floating objects to increase the encounter rate between isolated individuals or small schools and other schools to constitute bigger schools that are more efficient for the survival of the species (Fréon and Dagorn 2000). Castro et al. (2002), however, proposed alternative explanations for fish aggregation around floating objects, suggesting that drifting objects may drive and guide fish towards relatively productive areas, thereby enhancing the survival chances of larvae and juveniles. Regardless of the underlying hypotheses explaining these mechanisms, the fact remains that the number of IMUL vessels operating from Sri Lankan fishery harbours has shown a marked increasing trend in recent years (Table 5). As such, the proliferation of ring net fishing associated with floating objects is a matter of concern and should not be overlooked in efforts to inform future management. It must be noted, however, that the study period (March 2018 – May 2021) was the initial phase of the COVID-19 pandemic, which severely disrupted global fishing patterns. This must be a possible confounding factor for observed trends in the fishing patterns of IMULs.

Of the two dominant ring net target species, *D. russelli* stock is already optimally exploited. Further increase of fishing mortality is therefore not warranted, as this species is the most dominant in the ring net fishery landings (39%; Table 1), and increased exploitation might lead to depletion of spawning biomass below 50%. On the other hand, a sub-optimal level of exploitation of *E. bipinnulata* is reported, indicating the stock is still at a safe level.

However, as both species are exploited in the same fishing gear, it is impossible to achieve differential exploitation patterns for both species; an increase in the level of exploitation for *E. bipinnulata* invariably leads to over-exploitation of *D. russelli*. In the present analysis, however, the status of the fisheries of tuna and tuna-like species landed by other dominant fisheries of IMULs (i.e., drift gillnetting and longlining) was not evaluated based on length-based stock assessment as it was beyond the scope of the study.

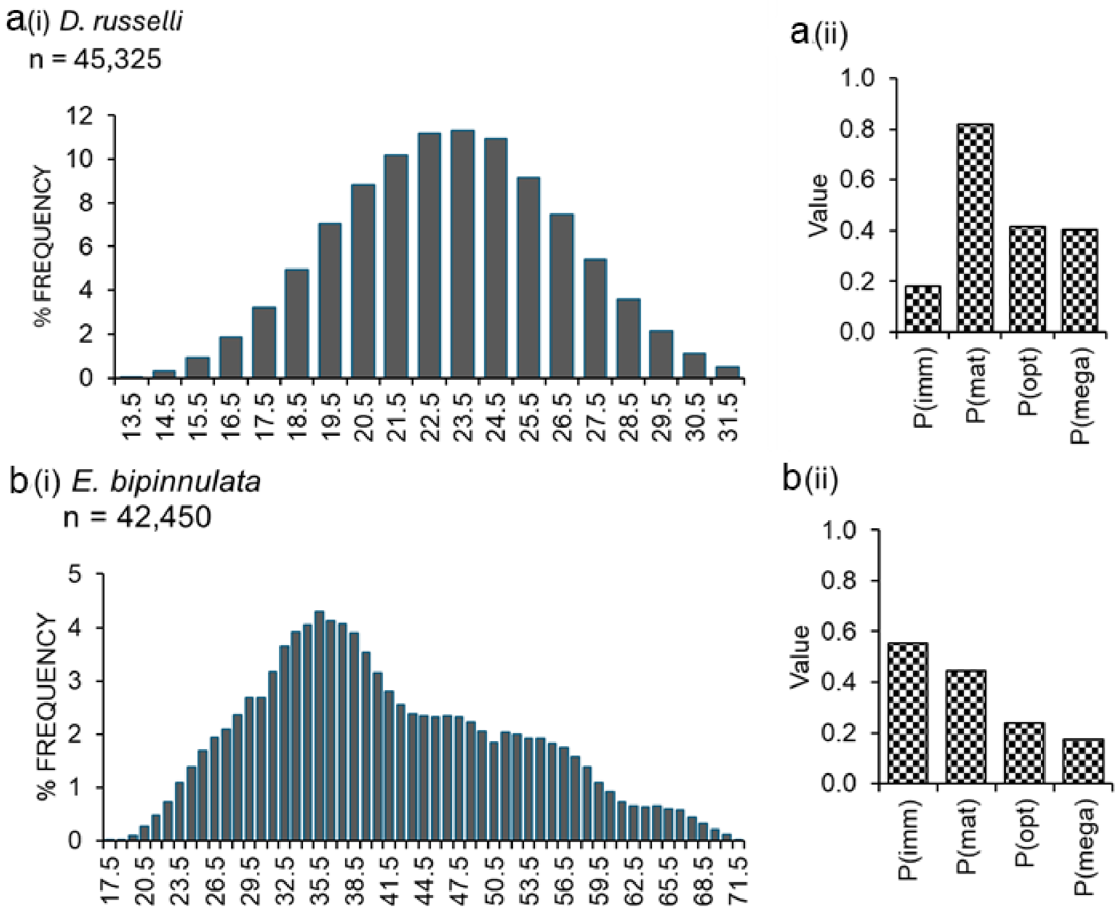

Fig 7. Overall length frequency distribution of [a(i)] *D. russelli* and [b(i)] *E. bipinnulata*, and LBIs of [a(ii)] *D. russelli* and [b(ii)] *E. bipinnulata*. For details, see text.

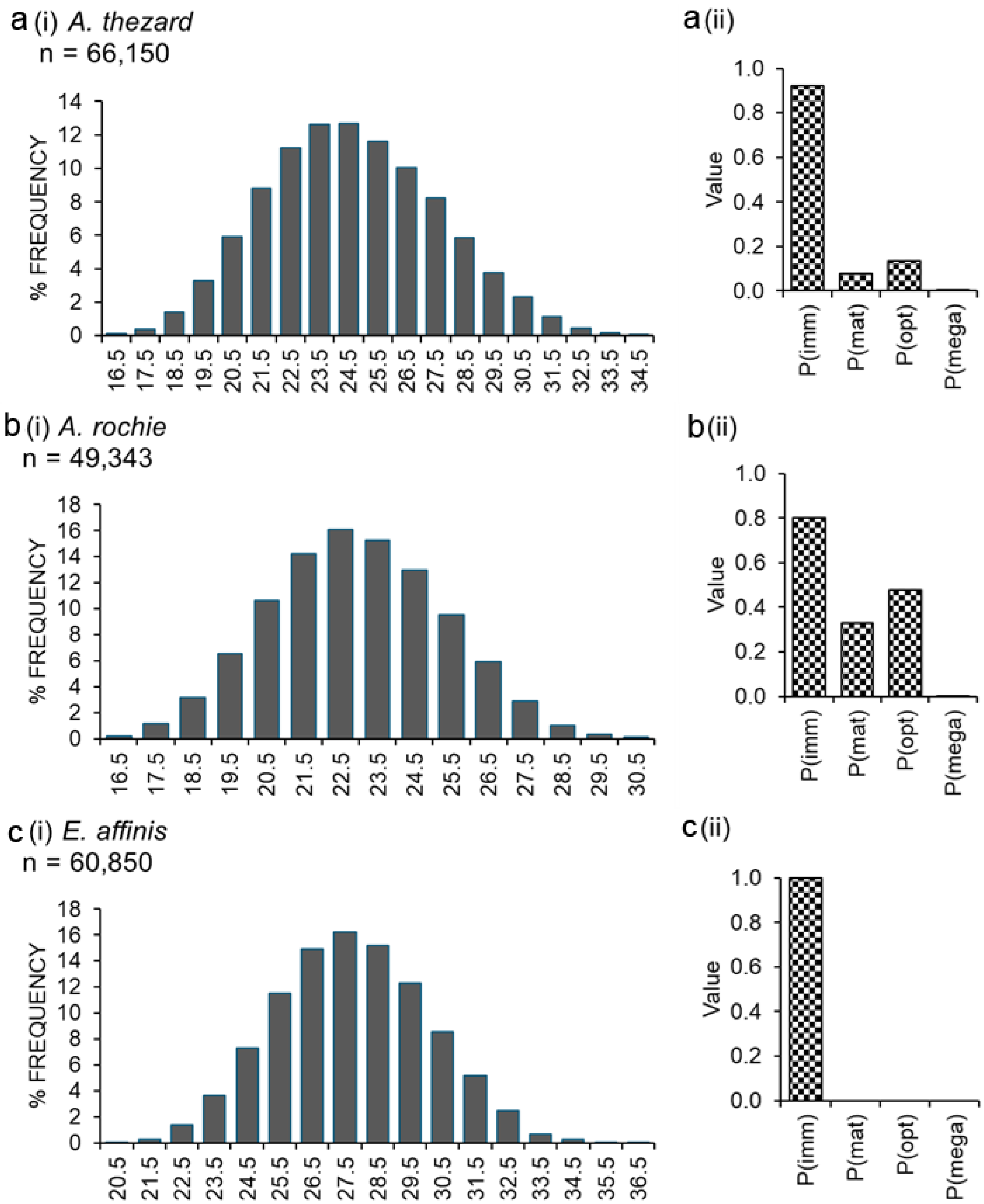

Fig 8. Overall length frequency distribution of [a(i)] *A. thezard*, [b(i)] *A. rochie* and [c(i)] *E. affinis*, and LBIs of [a(ii)] *A. thezard*, [b(ii)] *A. rochie* and [c(i)] *E. affinis*. For details, see text.

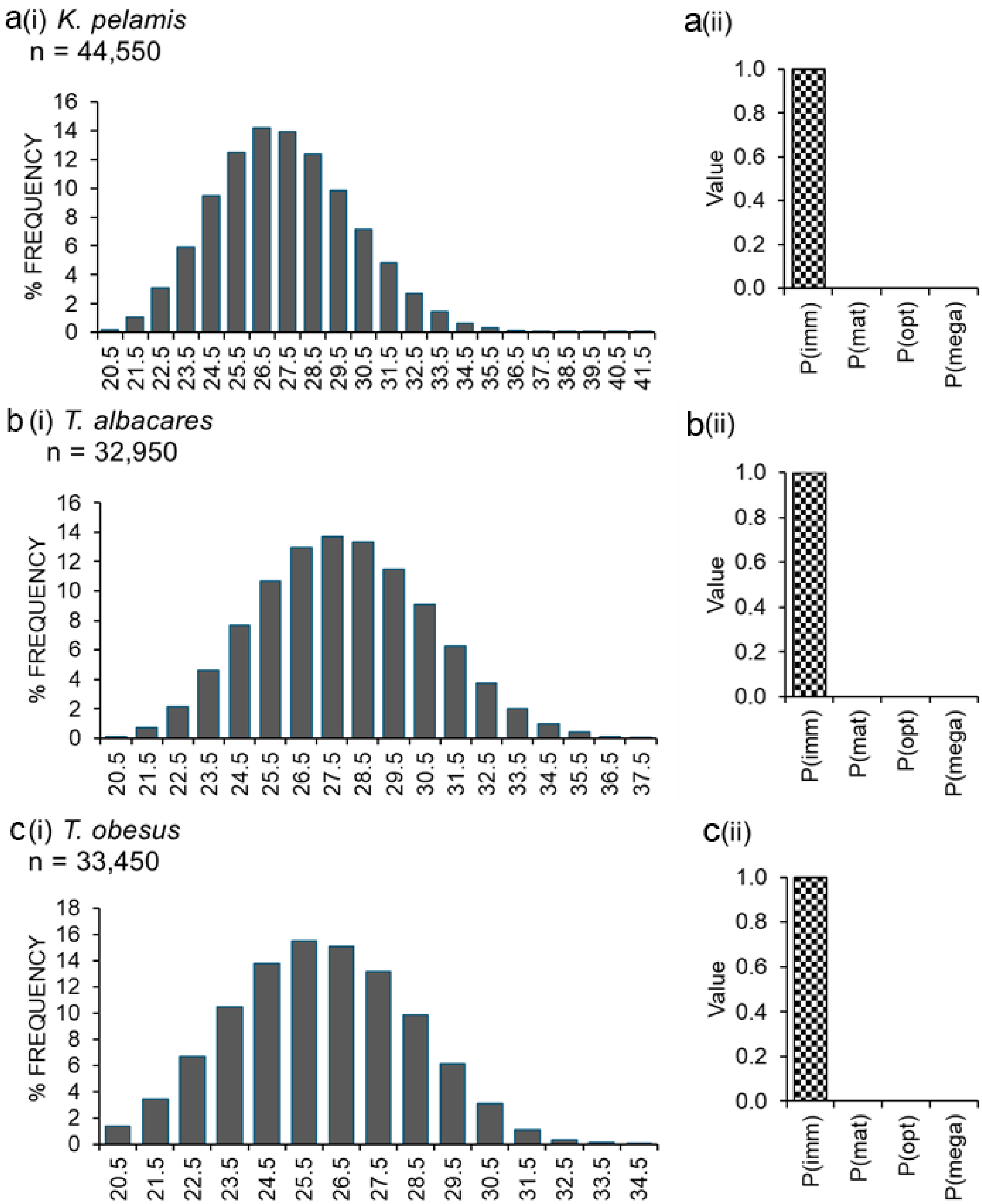

Fig 9. Overall length frequency distribution of [a(i)] *K. pelamis*, [b(i)] *T. albacares* and [c(i)] *T. obesus*, and LBIs of [a(ii)] *K. pelamis*, [b(ii)] *T. albacares* and [c(i)] *T. obesus*. For details, see text.

Table 5. Reported number of fishing trips of IMULs (2021 - 2024) and percentage increase (DFAR, 2025). RN: Ring net only; GN: Gillnet only; LL: Long line only; GNRN: Gillnet and Ring Nets; LLRN: Long line and Ring nets; LLGN: Long line and Gill nets

Gear type	2021	2022	2023	2024	% increase (2021-2024)
RN	2,805	2,947	5,518	8,416	200.0
GN	13,111	13,140	19,404	18,650	42.2
LL	10,112	10,181	14,375	14,495	43.3
GNRN	2,008	2,758	3,927	4,438	121.0
LLRN	7	26	111	108	1,442.9
LLGN	10,522	12,602	11,376	20,003	90.1

Three LBIs introduced by Froese (2004) which can be treated as length-based reference points (i.e., P_{mat}, P_{opt} and P_{mega}), are based on the facts that the length composition of fisheries landings should consist of (1) almost exclusively of mature individuals, (2) primarily of fish of the optimal size at which the highest yield is produced, and (3) size range of fish, which allows conservation of large, mature individuals (Cope and Punt 2009). Accordingly, management goals should be to allow the fishery to catch the majority of mature individuals (P_{mat}) within the range of P_{opt} and allow 30-40% of P_{mega} in the catch (Froese, 2004). Also, declining mega spawners is an indication of overfishing (Froese 2004), and accordingly, except *D. russelli* and *E. bipinnulata*, all pelagic fish species caught in the ring net fishery may be on the verge of overfishing. The near-zero P_{mega} for most species is expected in a fishery targeting aggregations (which often consist of mature fish), but the absence of mega spawners and dominance of immature individuals in the landings is a crucial indicator of the impact of ring net fishery on non-target pelagic species.

In the present study, of the two target species, *D. russelli* appears to be exploited at a sustainable level. In *E. bipinnulata* landings on the other hand, mega spawners are much lower (Figure 7b(ii)) while there is appreciably higher proportion of immature individuals. The three small tuna species caught as bycatch (*A. thezard*, *A. rochie* and *E. affinis*) caught in the ring net fishery consisted of immature individuals (Figure 8), and the proportions of mega spawners (P_{mega}) were much lower, registering zero for *E. affinis*. The cumulative contribution of these small tuna species was 18.7% (Table 1), and therefore, trends of overfishing as evident from LBIs are a matter of concern. Three species of large tuna caught as bycatch in the ring net fishery (*K. pelamis*, *T. albacares* and *T. obesus*) were juveniles, and as such, in all three species, length composition consisted of 100 % immature individuals (Figure 9). Except *K. pelamis*, which contributed 18.3 % of the landings, the percentage proportions of the other two tuna species were lower (*T. albacares*: 3.3 % and *T. obesus*: 3.0 %) (Table 1). The large tuna species that are caught in the ring net fishery essentially represent different life stages (i.e., juveniles) from those caught in drift gillnetting and longlining. Therefore, the impact of ring netting on large pelagic tuna stocks in the Indian Ocean requires further investigation, particularly given the alarming increase in ring net effort reported in this study (Table 5). According to Dagorn et al. (2012), on the other hand, catching juvenile tuna around floating objects does not necessarily result in overfishing of stocks. In fact, Dagorn et al. (2012) further suggested that small tunas that are caught in the fisheries associated with floating objects should not be treated as bycatch but should be included in the fisheries databases, which could be used for their stock assessment models.

Dupaix et al. (2024) mentioned that scientific evidence is insufficient to disentangle the effect of drifting objects and environmental factors on tuna stocks, which exhibit large-scale movements and behaviour. Gunawardane et al. (2024) have shown that the shifting of pelagic fish species, including tuna species, could be due to deoxygenation, which may have been triggered by increased sea surface and subsurface temperatures.

Natural and artificial floating objects are ubiquitous in the open oceans around the world, and numerous pelagic species, including tropical tuna, manifest an association with these floating objects (Castro et al. 2002; Dupaix et al. 2024). Pelagic fisheries associated with floating objects are reported in the Indian Ocean off Sri Lanka (Ariyarathna and Amarasinghe 2012), the Gulf of Thailand (Noranarttragoon et al. 2013), Panay Gulf, off the Philippines (Mitsunaga et al. 2013), and major species caught in such fisheries (e.g., *D. russelli*, *E. bipinnulata*, *Canthidermis maculatus*) in various open sea areas of the Indian Ocean are identical (Amandè et al. 2008). Since the 1980s, drifting fish aggregation devices have been widely used in tuna purse seine fisheries as a means of fisheries enhancement (Davies et al. 2014). An analysis of the status of five tuna fish stocks from both the Eastern and Western Indian Ocean indicated that all tuna stocks in both regions were overfished (Nisar et al. 2021). Artetxe-Arrate et al. (2021), based on a comprehensive review of the biology, ecology, and stock structure of tropical tuna species in the Indian Ocean, concluded that there is a clear lack of ocean basin-scale studies on skipjack, yellowfin and bigeye tuna life history, and that these knowledge gaps should be addressed to ensure a sustainable and effective management of these species.

Attraction of pelagic social species to the floating objects is reported to be influenced by two factors: (1) the size of the population, and (2) the number of floating objects, where greater aggregation is evident in situations of low density of floating objects and vice versa (Sempo et al., 2013). Proliferation of floating objects may therefore not increase the overall aggregation of fish around floating objects as a whole. There were some postulations that in the pelagic fish species that are attracted to natural or artificial floating objects, behaviour and biology could change adversely through the establishment of an ‘ecological trap’ (Marsac et al., 2000; Hallier and Gaertner, 2008). However, Dagorn et al. (2012) mentioned whether such floating objects act as ecological traps for fish would require further studies. Apart from natural floating objects, fisheries authorities of many maritime countries take steps to deploy drifting fish aggregation devices (FADs or artificial floating objects) to facilitate catching of pelagic fish species.

However, introducing FADs might result in changes in the habitat, and as such, monitoring the number of FADs is extremely important to quantify their impact and identify appropriate mitigatory measures. Regional Fisheries Management Organizations (RFMOs) should insist all member countries to establish mandatory FAD management plans, particularly since, under appropriate management regimes, FAD fishing could be both ecologically and economically sustainable (Dagorn et al., 2012). In general, minimum size limits based on L_m and/or L_c, gear modifications to increase mesh size in ring nets to allow juveniles to escape, and effort control through a licensing mechanism to limit the number of ring net operations are the possible management options. Perhaps, in the Sri Lankan scenario, the most feasible option is to control the amount of fishing through a licensing mechanism.

Schiller et al. (2025) highlighted that despite the regulatory processes being in place to control coastal pollution and prevent damage to sensitive habitats due to losses of FADs, there are persisting concerns and challenges over their unregulated deployment, unsustainable bycatch, and weak industry accountability. It has been reported that globally, although fisheries associated with floating objects have increased dramatically during the recent past, boosting the productivity of tuna fisheries, they may cause a risk of overfishing, and therefore, immediate regulatory measures are warranted to be implemented for these fisheries (Tidd et al., 2023). This is of particular importance due to the fact that although the two main target species in the flotsam-associated ring net fishery, *D. russelli* and *E. bipinnulata* are optimally exploited, proliferation of this fishery is a matter of concern regarding the risk of overfishing of bycatch species, particularly juvenile tunas, most notably *K. pelamis*. Also, from the economic point of view, greater efficiency of FAD fishing needs to be balanced with potential catch limitations for tuna fisheries in the Indian Ocean that may be imposed due to potential overfishing (Guillotreau et al., 2024).

CONCLUSIONS

The flotsam-associated encircling fishing operations, locally known as ring net fisheries, target shade-loving fish species such as *D. russelli* and *E. bipinnulata*, which aggregate under the floating objects. In these ring net fisheries, juveniles of non-target species, mainly small and large tuna species, are also caught as bycatch. Length-based stock assessment revealed that *D. russelli* stock is optimally exploited and further increases in fishing mortality are therefore not warranted. A sub-optimal level of exploitation of *E. bipinnulata* is evident from the analysis, indicating the stock is still at a safe level. According to length-based indicators (LBIs), proportions of mega spawners (i.e., proportion of fish bigger than the mean length at first capture) of both small and large pelagic tuna species were much lower or zero, while those of immature fish in the landings were much higher, indicating potential adverse impacts of ring netting on those fish stocks. Although there are claims that catching juvenile tuna around floating objects does not necessarily result in overfishing of stocks, the impact of ring netting on large pelagic tuna fish stocks in the Indian Ocean needs to be investigated further, especially because the massive increase in ring net effort reported in this study is most alarming. This is particularly due to the reason that, according to some studies, there is a risk of overfishing of tuna stocks due to the uncontrolled increase of such fisheries. Apart from natural floating objects, fisheries authorities of many maritime countries take steps to deploy drifting fish aggregation devices (FADs) to facilitate the catching of pelagic fish species. However, introducing FADS might result in changes in the habitat, and as such, monitoring the number of FADs is extremely important to quantify their impact and identify appropriate mitigatory measures.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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Appendix I TL-FL relationships (www.fishbase.org), estimated TL_∞ and M estimated using TL_∞ (Pauly 1980) with habitat temperature of 27°C. TL – Total length in cm; FL – Fork length in cm; M – Natural mortality

Species	TL = a +b FL	FL_∞	TL_∞	M from TL_∞
Decapterus russelli	TL =-0.0464+1.097 FL	33.7‡	36.9	1.31
Elegatis bipinnulata	TL = 0 + 1.1875 FL	75.7‡	89.9	0.69
Auxis thezard	TL = 0 + 1.0655 FL	51.0‡	54.3	0.748
Auxis rochei	TL = 0 + 1.042 FL	42.5‡	44.3	1.87
Euthynnus affinis	TL = 0.413 + 1.094 FL	78.9‡	86.7	1.03
Katsuwonus pelamis	TL = 2.311 + 1.049 FL	82.7*	89.1	0.80
Thunnus albacares	TL = 4.145 + 1.049 FL	181.9*	195.0	0.51
Thunnus obesus	TL = 0 + 1.10 FL	205.5*	226.1	0.34

‡ Estimated from FiSAT II and TropFishR
* Estimated from Equation 6