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Assessing Codend Mesh Selectivity: Comparing Diamond and Square Mesh Codend in the Red Sea Shrimp Trawl Fishery of Saudi Arabia

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Abstract: This study assessed catch composition, size selectivity, and fishing efficiency of demersal trawls targeting penaeid shrimp species in the Red Sea. It first compared the currently used diamond mesh codends in two fishing areas, Al Qunfudhah and Jazan, and then compared alternative square mesh codends to diamond mesh codends in Jazan. A total of 33 valid hauls were conducted in 2023, yielding 10,869 kg of total catch. The results showed that the square mesh codend significantly improved size selectivity, particularly for *Penaeus semisulcatus* and *Metapenaeus monoceros*, with L_{50} (50% retention length) values closer to their size at first maturity. The fishing efficiency indicators revealed a reduced retention probability for undersized individuals with square mesh codends. Additionally, bycatch discard rates decreased, indicating potential benefits for ecosystem conservation. This study suggests incorporating square mesh codends into fishery management regulations to enhance size selectivity and reduce bycatch during Red Sea shrimp trawling. Establishing a legal minimum landing size requirement is recommended to complement these efforts and promote sustainable fishing practices.

Keywords: size selectivity; sustainability; trawl fisheries; bycatch; Red Sea

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1. Introduction

Penaeid shrimps (Family Penaeidae) are among the most commercially important species for capture fisheries in the Red Sea [1–3]. Penaeid shrimp production derived from global fishing has shown a notable decline over the years. In 1982, worldwide landings reached a maximum level of 327,871 metric tons; however, by 2021, they had decreased by over 50% to 165,196 metric tons [4] The factors contributing to this decline, as outlined by [5,6], include overfishing, the use of poor selective gears, bycatch, and habitat degradation.

Trawling, the most popular and efficient method for harvesting shrimp, has sparked controversy due to its adverse effects on marine biodiversity and the seabed. Shrimp trawling is considered a relatively non-selective fishing method because it typically results in the retention of large amounts of bycatch within the codend, encompassing various species differing in size and shape. In this fishery, bycatch refers to anything other than the targeted and commercially valuable shrimp species that fishers aim to capture. Bycatch

may include fish, crabs, sea turtles, sharks, rays, coral fragments, seaweed, and seabed debris [7,8]. Some bycatch species are retained by fishers for sale or personal consumption. However, many unintentionally caught species, often of little to no commercial value or deemed inedible, are discarded at the sea. These discards also include sharks, rays, and turtles, which are considered vulnerable and legally protected, thereby prohibiting their capture [9]. Additionally, discards often consist of juvenile or undersized individuals with minimal or no market value due to their small size [8].

Shrimp trawling on the Red Sea coast of Saudi Arabia involves a fairly large fleet, comprising 146 vessels in Jazan and 24 vessels in Al Qunfudhah, each equipped with main engines ranging from 240 to 540 horsepower [10]. The fishing season extends from 1 September to 31 March with varying fishing times; trawling occurs late evening and night in September, while it is conducted exclusively at night for the remaining six months. Operations commence after sunset, continue throughout the night, and end before sunrise. The depths targeted for trawling usually range from 12 to 24 m, although vessels may operate at depths between 10 and 40 m. A typical fishing day consists of 4 to 5 operations, with each haul lasting 3 to 4 h. The trawling grounds consist primarily of sandy areas with occasional patches of muddy seafloors. Vessel lengths overall (LOA) vary from 12.0 to 23.0 m, predominantly constructed from wood and sheet metal. Towing speeds average 3.0 knots, utilizing towing warps of 140 m in length for depths of 20 to 24 m [10]. The doors used for trawling are mostly V-shaped stainless steel or rectangular, flat, wooden otter boards, reinforced with an iron frame, with dimensions and weights tailored to optimize efficiency [11]. Overall, these parameters outline a comparable operational framework for shrimp trawling in the Al Qunfudhah and Jazan regions, providing insights into vessel characteristics, environmental conditions, and fishing practices.

Various technical and biological measures are currently being implemented along the Red Sea coast of Saudi Arabia to ensure the protection and long-term sustainability of demersal shrimp and fish stocks in the region. These measures include restrictions on the number and size of trawl vessels as well as regulations governing where and when trawling can take place. Current Saudi Arabian legislation on trawl codends specifies only a minimum mesh size of 40 mm for the Red Sea. However, codends with various mesh sizes and shapes produce distinct selectivity parameters for each species. Therefore, selecting a specific target species is essential for determining the appropriate mesh size or shape (diamond or square). A practical compromise is to find an optimal mesh size or shape where the 50% retention length (L_{50}) matches the Minimum Landing Size (MLS) or Minimum Conservation Reference Size (MCRS) of the target species. This approach helps minimize unwanted bycatch while ensuring compliance with target species-specific regulations. According to Saudi Arabian fishery regulations [12], MLS is enforced for only a limited number of fish species (35 in total), and few of these are caught in shrimp trawls. Additionally, as in many regions of the world, there are no MLS requirements for commercial shrimp species in Saudi Arabia's fishery legislation. Recent biological studies conducted by KAUST in the Red Sea [10] have established the median Sexual Maturity Size (SMS) for several commercially important shrimp species. These SMS values are 22.3 mm CL for *Penaeus semisulcatus*, 21.1 mm CL for *Metapenaeus monoceros*, 23.6 mm CL for *Penaeus hathor*, and 34.7 mm CL for *Penaeus pulchricaudatus*.

In the Red Sea, a wide variety of species are caught simultaneously by shrimp bottom trawls, characterizing the fishery as multi-species in nature. Therefore, it is not feasible to regulate selectivity for all these species solely by establishing a minimum mesh size regulation. Depending on the amount of catch, diamond-shaped meshes in a codend stretch during towing, reducing selectivity compared to open square meshes [13–15]. Furthermore, each species has different growth characteristics, body shape, and size at maturity, similar to the situation in the Mediterranean Sea [16–18].

The integration of square mesh codends, panels, or windows in demersal trawls has emerged as a pivotal strategy to mitigate the unwanted bycatch of non-target species, such as immature commercial fish species and juvenile shrimp, thereby contributing to ecosys-

tem conservation and sustaining fishery resources. Implementing square mesh riggings can function either as a mandatory requirement or as an optional measure, depending on regional regulations and specific fishery dynamics. Numerous studies have demonstrated the effectiveness of such technologies in minimizing bycatch while optimizing the retention of target species, highlighting their significance in promoting more selective and environmentally responsible fishing practices [14,19–22]. This approach represents a crucial step toward achieving sustainable fisheries management and ensuring the long-term viability of marine ecosystems. As a result, numerous applications worldwide have aimed to improve the selectivity of bottom trawls through the mandatory or optional use of square mesh codends, panels, or windows in demersal trawls. In the Mediterranean waters of the European Union, Council Regulation (EC) No 1967/2006 of 21 December 2006 [23] states that a diamond mesh codend of 50 mm may be used as an alternative to the 40 mm square mesh codend at the duly justified request of the vessel owner. Currently, the Spanish bottom trawl fleet uses 40 mm square mesh codends [24]. Similarly, in Türkiye, the regulation mandates that the codend mesh size of demersal trawl nets should not be smaller than 44 mm for diamond mesh and 40 mm for square mesh [25]. To ensure the recovery of Celtic Sea cod (*Gadus morhua*), another Council Regulation (EU) 2020/900 of 25 June 2020 [26] requires the continued use of a 100 mm diamond mesh codend with a 160 mm square mesh. However, no information is currently available on the selectivity performance of diamond mesh codends used in the Red Sea or their alternative square mesh codends.

Effective fisheries management requires that fishing gear be designed to be selective [27]. Improved selectivity helps minimize the capture of juvenile fish by regulating the size at which they are first caught. This, in turn, increases the yield of the targeted species for each recruit while reducing the discarded bycatch [28]. Although it is known that the selectivity of shrimp trawl nets is poor, the selectivity parameters of the nets used in the Red Sea for shrimp and fish species have never been studied until now. To this end, the objectives of this study are twofold, with possible implications for future management measures: (i) to determine the selectivity characteristics of the currently used 40 mm diamond mesh (40D) codend in shrimp trawls in two different fishing areas of the Red Sea, and (ii) to assess the selectivity characteristics of the 40 mm square mesh (40S) codend as a potential alternative to enhance the size selectivity of *P. semisulcatus* and *M. monoceros*, as well as other commercial shrimp species such as *P. hathor*, *P. pulchricaudatus*, and *Penaeus indicus*.

2. Material and Methods

2.1. Study Area, Trawl Rigging, and Data Collection

Two surveys were conducted using shrimp trawl (otter bottom trawl): one between 1 May and 6 May 2023 in Al Qunfudhah and the other between 28 May and 5 June 2023 in Jazan (Figure 1). Al Qunfudhah trials were carried out with the ABU-SALIM 3 (75707), a typical side trawler measuring 16.8 m in LOA and powered by a 360 HP engine. For Jazan trials, the ALSALAM ALEASHAR (44256), a stern trawler measuring 17.0 m in LOA and equipped with a 550 HP engine, was employed. The characteristics of the trawl hauls in the trials were precisely aligned with those in commercial fishing, e.g., locality, haul duration, towing speed, and trawl net. All hauls were conducted at night, with a consistent towing duration of approximately 3 h and an average towing speed of 3.0 knots. During the trials, 12 valid hauls were completed with the diamond mesh codend (40D) in Al Qunfudhah and 11 valid hauls in Jazan, while 10 valid hauls were completed with the square mesh codend (40S) in Jazan.

Conventional two-panel asymmetric high-opening shrimp bottom trawl nets were used in the trials [10]. Long-winged shrimp trawl nets employed along the Red Sea coast of Saudi Arabia have a smaller mesh size in the front section (wings and squares) and two short bridle riggings, making them ideal for catching shrimp. Detailed information on the rigging and operational features of the nets can be found in Anonymous [29] and KBD [11]. The trawl net used in Al Qunfudhah was medium-sized, with a total length of 34.8 m, while the net used in Jazan was larger, with a total length of 49.9 m. All nets were constructed

using a multi-monofilament polyethylene (PE) netting material. The otter boards used in Al Qunfudhah weighed 130 kg each, whereas those in Jazan weighed approximately 300 kg each.

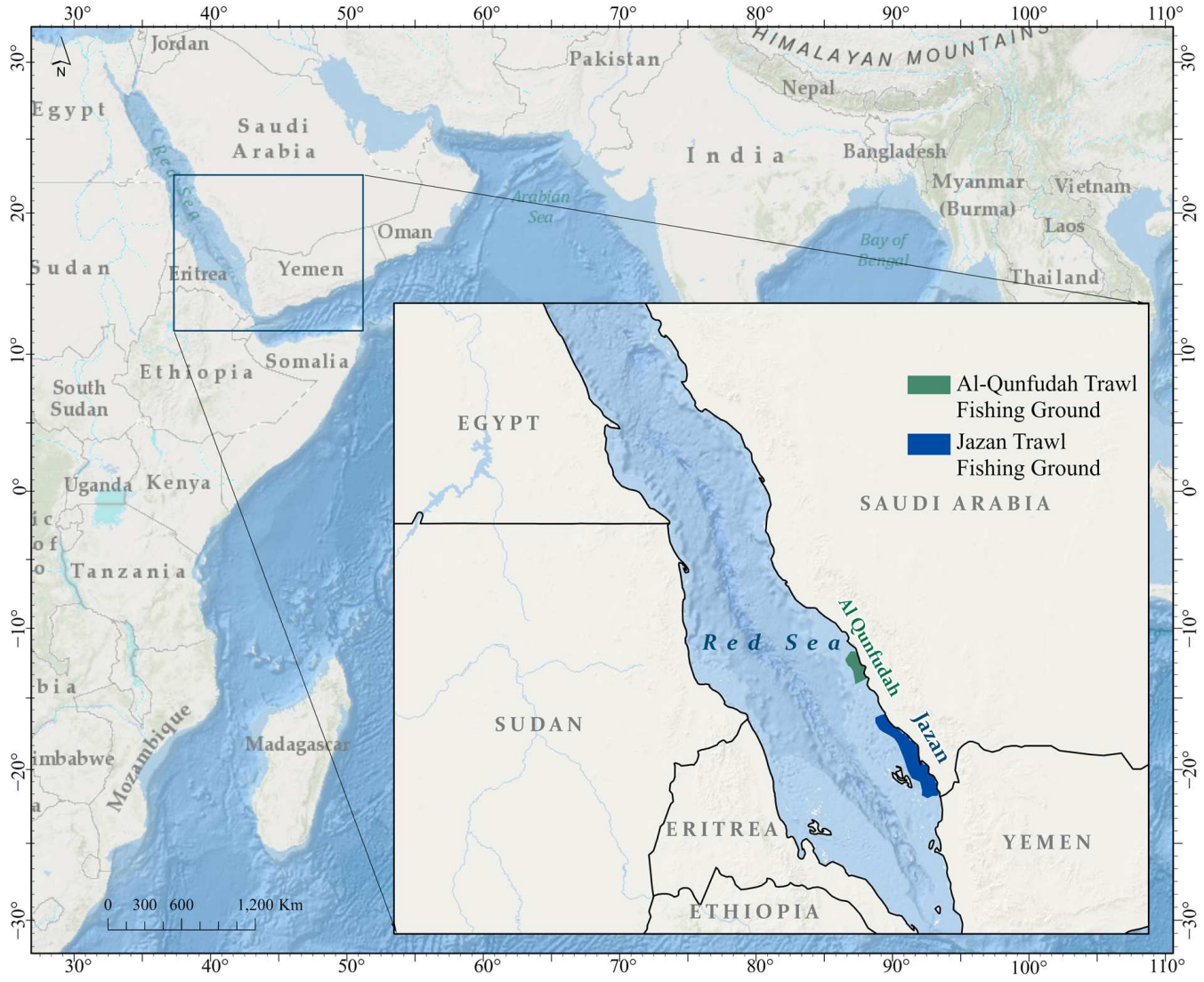


Figure 1. Location of the study areas where the sea trials were conducted.

There are several attachments to the codend of shrimp trawl nets, including a lifting bag for protection, codline, and strops. The codend is 160 meshes long and 136 in circumference, with a mesh size of 40 mm. In contrast, its lifting bag is 20 meshes long and 60 meshes in circumference (120 mm mesh size). The stretched circumference of the codend is 5.5 m, while that of the lifting bag is 7.2 m. These dimensions suggest that the meshes of the lifting bag do not have any masking effect on the opening of the codend meshes [30]. In addition, there are three ropes attached to the trawl nets. The lifting strop (2nd rope) on the lifting bag and the codend strop (1st rope) are crucial for safely retrieving the codend onboard during side trawling operations. However, the lifting strop on the lifting bag was removed for operational reasons during the selectivity trials to ensure the proper functioning of the cover. The codline at the end of the codend is easy to open on the deck when the codend is full of catch. Since this attachment is at the end of the codend, it does not negatively impact codend mesh selectivity.

Due to the lifting strop at the beginning of the codend, the cover was designed to fit the last 5 m of the codend and was mounted accordingly. Both diamond and square mesh

codends were made with the same netting specifications: a nominal 40 mm mesh size and Ø 0.05 × 21 × (3) twine diameter, with identical dimensions (length and circumference). The square mesh codend is prepared by cutting it from a piece of diamond mesh netting. Details of the trawl nets and codends, lifting bags, and cover specifications are given in Table 1. It is important to note that the number of meshes around the codend (circumference) differed between the trawls in Al Qunfudhah and Jazan. Consequently, the number of meshes around the covers was also different. The stretched cover width-to-codend ratio was approximately 1.5, which was achieved by adjusting the number of meshes around the cover circumference, according to Holden [31].

Table 1. Details of codends, lifting bags, and cover specifications used in the selectivity trials.

	Al Qunfudhah	**Jazan**	
Trawl fishing circle	800 mesh–40 mm	680 mesh–60 mm	
Trawl net total length	34.8 m	49.9 m	
Funnel circumference	140 meshes	200 meshes	
Codend mesh shape	Diamond	Diamond	Square
Codend mean mesh size (mm)	37.8 ± 0.6 mm	37.9 ± 0.8 mm	38.1 ± 0.9 mm
Codend length	5.0 m	5.0 m	5.0 m
Codend material	PE 40 mm 3 × 21 × 0.05	PE 40 mm 3 × 21 × 0.05	
Codend nominal mesh size	40 mm	40 mm	
Codend circumference	136 meshes	200 meshes	150 meshes
Lifting bag length	2.4 m	3.2 m	
Lifting bag material	PA Ø 4	PP Ø 4	
Lifting bag mesh size	120 mm	100 mm	
Lifting bag circumference	60 meshes	100 meshes	
Cover mesh size	18 mm		
Cover material	knotted 210 d/12		
Cover length	7.5 m		
Cover circumference	450 meshes	600 meshes	
Cover/Codend ratio	1.5	1.4	

To determine the mean mesh size of each codend, a total of 60 stretched mesh openings were measured near the aft (3 lines of 20 meshes in the towing direction) using a caliper rule with a 4 kg weight tied vertically to the stationary jaw of the rule [32]. The results of the mean mesh sizes and standard deviations are presented in Table 1.

A codend cover made of Polyamide (210 d/12 (denier/ply), no twine thickness, and 18 mm mesh size) (Table 1) was used to collect fish escaping from the codend (covered codend technique) [30]. The cover was 7.5 m long, 450–600 meshes in circumference, and supported by a hoop to coincide with the expanding catch at the back of the codend. This design avoids the masking effect and ensures water flow between the codend and the cover. Stewart and Robertson [33] and Reeves et al. [34] reported that the masking effect of the cover might influence the selectivity of the codend. This effect has been minimized by mounting hoops to hold the cover netting away from the codend meshes [16,35,36].

The catches from the codend and cover of each haul were kept separately onboard (Figure 2). If the catch included a shark, ray, or turtle, they were immediately attended to, and after recording their numbers and weights, they were promptly released back into the sea. Species in the codend catch were manually sorted by fishers into targeted shrimp, retained, and discarded categories. The same procedure was applied to the cover catch, but only for the retained species. All taxa were identified to the lowest possible level, and their

weights were recorded. The carapace length (CL) of all commercial shrimps in both codend and cover catch was measured individually to the nearest 0.01 cm using a digital caliper to obtain the length frequency distribution. When the total number of specimens for any species exceeded 500, a random subsample of at least 500 shrimp was used for individual CL measurements.



Figure 2. Cover and square mesh codend catches emptied separately on the deck of the trawler.

2.2. Size Selectivity Analysis

The experimental design allowed for the analysis of the collected catches as binominal data, where the specimens were either retained by the codend or captured in the cover. The probability of finding a shrimp of length l in the codend in haul j is expressed by the function $r_j(l)$. The purpose of the analysis was to estimate the values of this function for all relevant sizes [37]. Data analysis for each codend was carried out separately using the method described below.

Binominal data were used to estimate the size selection of the codends (i.e., length-dependent retention probability). Size selectivity is expected to vary between hauls, even with the same codend [38]. In this study, as proposed by Millar [39], we focused on the average size selection across all hauls combined, providing information about the average consequences of the size selection process when different codends are applied in fisheries. Different parametric models $r_{codend}(l, v_{codend})$ were tested for the codend size selection, where v_{codend} is a vector of model parameters. The analysis aimed to estimate the values of v_{codend} that would most likely produce the observed experimental data (combined from all hauls). For this purpose, the following expression was minimized, corresponding to the maximum likelihood of the observed experimental data:

$$\sum_{j=1}^{m} \sum_{l} \left\{ nC_{lj} \times ln(r_{codend}(l, v_{codend})) + nCC_{lj} \times ln(1.0 - r_{codend}(l, v_{codend})) \right\} \quad (1)$$

where nC_{lj} and nCC_{lj} denote the number of shrimps caught in haul j with length l collected in the codend (C) and cover (CC), respectively. The outer summation in Function (1) comprises the hauls conducted with a specific codend and the inner summation over length class l in the data. Four different models were chosen as primary candidates to describe $r_{codend}(l, v_{codend})$ for each codend and species: Logit, Probit, Gompertz, and Richards. The first three models were fully described by the two selection parameters L_{50} (CL of shrimp

with a 50% probability of being retained) and *SR* (difference in CL between shrimp with 75% and 25% probability of being retained). The Richards model requires an additional parameter ($1/\delta$) that describes the asymmetry of the curve. The formulas and further information for the four selection models can be found in Lomeli [40].

$$r_{codend}(l, v_{codend}) = \begin{cases} Logit(l, L_{50}, SR) = \frac{exp\left(\frac{\ln(9)}{SR} \times (l - L_{50})\right)}{1.0 + exp\left(\frac{\ln(9)}{SR} \times (l - L_{50})\right)} \\ Probit(l, L_{50}, SR) \approx \Phi\left(\left(\frac{1.349}{SR} \times (l - L_{50})\right)\right) \\ Gompertz(l, L_{50}, SR) \approx \exp\left(-exp\left(-\left(0.365 + \frac{1.573}{SR} \times (l - L_{50})\right)\right)\right) \\ Richards\left(l, L_{50}, SR, \frac{1}{\delta}\right) = \left(\frac{exp\left(logit\left(0.5^{\delta}\right) + \left(\frac{logit\left(0.75^{\delta} - logit\left(0.25^{\delta}\right)\right)}{SR}\right) \times (l - L_{50})\right)}{1 + exp\left(logit\left(0.5^{\delta}\right) + \left(\frac{logit\left(0.75^{\delta} - logit\left(0.25^{\delta}\right)\right)}{SR}\right) \times (l - L_{50})\right)}\right) \end{cases} \quad (2)$$

The term Φ in the above probit model is the cumulative density function for the normal distribution. Evaluating a model's ability to describe data sufficiently is based on calculating the corresponding *p*-value, which expresses the likelihood of obtaining a discrepancy between a fitted model and observed experimental data as large as or larger than that observed by chance. For a fitted model to be considered a suitable candidate for size-selection data, the *p*-value should not be below 0.05 [30]. In cases of a poor fit statistic (*p*-value < 0.05), the residuals were inspected to determine whether the poor result was due to structural problems when modeling the experimental data using different selection curves or due to data overdispersion [30]. The selection of the best model was based on Akaike Information Criterion (*AIC*) values, with the model having the lowest *AIC* value being chosen [41].

Once the specific size selection model was identified for a particular codend, bootstrapping [42] was applied to estimate the confidence limits of the average size selection curve. The software tool SELNET [37] was used for size selection analysis, implementing a double-bootstrap method to obtain confidence intervals (CIs) for the size selection curve and corresponding parameters. As described by Millar [39], this bootstrapping approach accounted for both within-haul and between-haul variations. To address between-haul variations, an outer bootstrap resample with replacements from a group of hauls was included in the procedure. Within each resampled haul, data for each length class were bootstrapped in an inner bootstrap with replacement to account for within-haul variation. Each bootstrap resulted in a 'pooled' set of data, which was analyzed using the identified selection model. Thus, each bootstrap run produced an average selection curve. For each analyzed species, 1000 bootstrap resamplings were conducted to estimate the 95% nonparametric CIs [37,42].

2.3. Inferring the Differences in Size Selectivity between Codends

To determine the differences in retention probabilities, the following generic delta curve ($\Delta r(l)$) was used:

$$\Delta r(l) = r_{test}(l) - r_{baseline}(l) \quad (3)$$

where on a case-by-case basis, $r_{test}(l)$ is the retention probability of a specific codend with a modified design and $r_{baseline}(l)$ is the retention probability value of the baseline design in each pairwise comparison. The 95% nonparametric CIs for $\Delta r(l)$ were obtained based on the results of the two bootstrap populations (1000 bootstrap resamplings in each). As bootstrap resamplings were random and independent for the two groups of results, it was valid to generate a new bootstrap population for the difference (3) based on the two generated bootstrap files [15]:

$$\Delta r(l)_i = r_{test}(l)_i - r_{baseline}(l)_i \;\; i \in [1 \ldots 1000], \quad (4)$$

where i is the bootstrap repetition index. Significant differences in the size selection of each length class between codends were identified if the 95% CIs for the delta curves included the 0-axis for this length class.

2.4. Estimation of Fishing Efficiency Indicators

To investigate how applying the considered codends would affect the capture pattern in fisheries, the values of three exploitation pattern indicators, nP^-, nP^+, and $nDiscard$, were estimated. These indicators are often used in fishing gear size selectivity studies to supplement assessments based solely on selectivity curves [43–49]. To estimate these performance indicators, the size selection curves predicted for each codend were first applied to the population of the studied species entering the fishing gear. This was obtained based on the data from all hauls for all codend designs during a survey period by summing the catches in codends and covers [50]. Uncertainties in populations were obtained by double bootstrapping, following the approach described in Melli et al. [47]. Then, the percentage of individuals below (nP^-) and above (nP^+) the SMS due to a lack of MLS for each species was calculated. Ideally, the nP^- and $nDiscard$ ratio should be low (close to 0), while nP^+ should be high (close to 100). The indicators for different codends were estimated by:

$$\begin{aligned} nP^- &= 100 \times \frac{\sum_{l<SMS}\{r_{codend}(l,v_{codend}) \times nPop_l\}}{\sum_{l<SMS}\{nPop_l\}}, \\ nP^+ &= 100 \times \frac{\sum_{l>SMS}\{r_{codend}(l,v_{codend}) \times nPop_l\}}{\sum_{l>SMS}\{nPop_l\}}, \\ nDiscardRatio &= 100 \times \frac{\sum_{l<SMS}\{r_{codend}(l,v_{codend}) \times nPop_l\}}{\sum_{l}\{r_{codend}(l,v_{codend}) \times nPop_l\}} \end{aligned} \quad (5)$$

All indicators (nP^-, nP^+, and $nDiscard\ Ratio$) were estimated with uncertainties for each codend and population scenario, using a bootstrap set for $r_{codend}(l, v_{codend})$ and $nPop_l$. Based on Herrmann et al. [15], the bootstrap set to calculate the indicator values was obtained from each bootstrap resampling result, by applying $r_{codend}(l, v_{codend})$ and $nPop_l$ simultaneously in Equation (5). Finally, 95% CIs were obtained for each indicator from the resulting bootstrap set. All indicator analyses were conducted using the software SELNET [37]. All graphs were plotted using R (v. 4.2.1) with RStudio (v. 2023.03.0) software [51] using the ggplot2 (v.3.4.1) package [52]. A comparison of the indicators between the tested codends was based on the overlap of their CIs.

3. Results

3.1. Catch Composition

In the fishing trials, a total of 33 valid hauls were conducted, resulting in the capture of 9963.8 kg (301.9 kg/haul) of aquatic life. The target shrimp species comprised 9.58% of the total catch by weight, and the remaining 90.42% were non-targeted aquatic species (bycatch). The proportional distribution of the target species in the total catch was 8.41% for *P. semisulcatus*, 0.28% for *M. monoceros*, 0.09% for *P. pulchricaudatus*, and 0.02% for *P. hathor*. Among the target species, *P. semisulcatus* was the most dominant species, accounting for 94.27% of the total catch by weight, while *P. hathor* was the rarest, comprising only 0.33%.

Analysis of bycatch distribution revealed that fish accounted for the largest share at 55.23%, followed by other categories (15.54%), vulnerable species such as sharks, rays, and turtles (9.33%), cephalopods (7.12%), and crabs (3.21%). The percentages by number and weight of the target shrimp species and other groups for each codend type are given in Table 2. As shown in the table, 85.3% of the catch by weight remained in the 40D codend in Al Qunfudhah, with only 14.7% escaping. In Jazan, these values were 73.2% and 26.8%, respectively, for the 40D codend. In contrast, while 49.1% of the catch remained on the 40S codend, 50.9% escaped. The use of a square mesh (40S) in the codend design increased the escape rate by 24% to 36% compared to the diamond mesh (40D) codend. For each species and group, the percentage of total weight was consistently higher than that of number for each codend (Table 2). Larger individuals with higher weights tended to remain in the codend, while smaller ones passed through to the cover, resulting in a lower total weight.

Similarly, the 40S codend positively contributed to the escape rate for both the target shrimp species and bycatch groups.

Table 2. Total number of individuals and total weights (g) of commercial shrimp species and aquatic groups in the codend and cover for each design. The group "others" includes all remaining taxa, excluding the target species and bycatch groups that have already been specified by their respective names in the table.

Locality	Al Qunfudhah (12 Hauls)				Jazan (11 Hauls)				Jazan (10 Hauls)			
Tested Codends	40 mm Diamond				40 mm Diamond				40 mm Square			
	Codend		Cover		Codend		Cover		Codend		Cover	
Species and Groups	Number	Weight (g)	Number	Weight (g)	Number	Weight (g)	Number	Weight (g)	Number	Weight (g)	Number	Weight (g)
Penaeus semisulcatus	6101	126,479	349	1770	32,512	385,615	1167	9103	22,987	309,147	9372	82,845
Metapenaeus monoceros	774	10,301	60	262	1627	7215	585	2103	783	2918	1743	7233
Penaeus pulchricaudatus	156	4386	0	0	109	1947	2	5	65	926	9	63
Penaeus hathor	130	1769			31	164	12	31	14	89	42	132
Fishes	136,478	1,748,836	89,571	459,593	103,457	808,611	264,572	625,526	32,470	691,570	425,954	1,168,694
Cephalopods	7952	365,748	1359	23,578	10,314	167,634	678	2143	5661	139,273	834	10,602
Crabs	791	12,816	113	347	1192	158,563	113	3433	1055	120,239	144	23,988
Others	36,562	533,874	27,198	75,927	43,368	328,573	105,082	165,237	10,354	146,995	119,569	297,471
Vulnerable species	69	456,272			35	352,530			63	121,263		
Total	189,012	3,260,482	118,650	561,476	192,645	2,210,852	372,211	807,582	73,452	1,532,421	557,667	1,591,028
Percentage distribution	%				%				%			
Species and Groups												
Penaeus semisulcatus	94.6	98.6	5.4	1.4	96.5	97.7	3.5	2.3	71.0	78.9	29.0	21.1
Metapenaeus monoceros	100.0	100.0			98.2	99.7	1.8	0.3	87.8	93.6	12.2	6.4
Penaeus pulchricaudatus	92.8	97.5	7.2	2.5	73.5	77.4	26.5	22.6	31.0	28.7	69.0	71.3
Penaeus hathor	100.0	100.0			72.1	83.9	27.9	16.1	25.4	40.2	74.6	59.8
Fishes	60.4	79.2	39.6	20.8	28.1	56.4	71.9	43.6	7.1	37.2	92.9	62.8
Cephalopods	85.4	93.9	14.6	6.1	93.8	98.7	6.2	1.3	87.2	92.9	12.8	7.1
Crabs	87.5	97.4	12.5	2.6	91.3	97.9	8.7	2.1	88.0	83.4	12.0	16.6
Others	57.3	87.5	42.7	12.5	29.2	66.5	70.8	33.5	8.0	33.1	92.0	66.9
Vulnerable species	100.0	100.0			100.0	100.0			100.0	100.0		
Total	61.5	85.3	38.5	14.7	34.1	73.2	65.9	26.8	11.6	49.1	88.4	50.9

A total of 78,630 shrimp specimens were used to determine size selectivity; of these, 7570 and 36,044 were caught in the 40D (codend + cover) in Al Qunfudhah and Jazan, respectively, while 35,016 were caught in the 40S (codend + cover). The total catches for the 40D codend in Al Qunfudhah were 6450, 834, 156, and 130 for *P. semisulcatus*, *M. monoceros*, *P. pulchricaudatus*, and *P. hathor*, respectively. Meanwhile, for the 40D in Jazan, the totals were 33,715, 2236, 106, and 28; for the 40S, they were 32,359, 2526, 74, and 56 for the same species. Due to the limited number of samples, further statistical evaluations were not performed for *P. pulchricaudatus* and *P. hathor*.

3.2. Size Selectivity

Based on the *AIC* values among the four candidate models, the Richards model provided the best fit for *P. semisulcatus* in the 40D codends in Al Qunfudhah and Jazan, as well as for the 40S codend in Jazan (Table 3). The Richard model significantly outperformed the other models with the lowest *AIC* value. Although the model described the experimental data adequately, the *p*-value was less than 0.05 (Table 3). This low *p*-value was due to overdispersion in the hauling data. Most of the observed data points fell within the 95% CIs range of the selectivity curve (Figure 3). The estimated L_{50} and *SR* values for the 40D codends were 1.31 cm and 0.52 cm CL in Al Qunfudhah and 1.46 cm and 0.40 cm in Jazan, respectively, for *P. semisulcatus* (Table 3). For the 40S codend in Jazan, the L_{50} and *SR* values were estimated as 1.96 cm and 0.58 cm CL. The estimated L_{50} values for *P. semisulcatus* in both the 40D and 40S codends were below the reported SMS for this species.

Table 3. Summary of the *AIC* values, selectivity parameters, and fit statistics of 40D and 40S mesh codends for *P. semisulcatus* in Al Qunfudhah and Jazan (L_{50}: 50% retention probability; *SR*: selection range; *df*: degrees of freedom. The values in parentheses are the 95% nonparametric confidence intervals).

Codends		40 mm Diamond		40 mm Square
Locality		Al Qunfudhah	Jazan	Jazan
AIC values	Logit	1680.48	8819.15	30,516.23
	Probit	410,349.69	2,340,572.21	30,274.86
	Gompertz	1860.63	10,067.95	31,251.33
	Richards	1511.11	7700.91	28,123.87
Selectivity parameters	L_{50} *	1.31 (1.24–1.45)	1.46 (1.35–1.56)	1.96 (1.86–2.07)
	SR *	0.52 (0.37–0.83)	0.40 (0.28–0.52)	0.58 (0.48–0.72)
	p-value	0.019	0.000	0.026
	Deviance	15.07	137.03	12.69
	df	6	6	5

*: carapace length in cm.

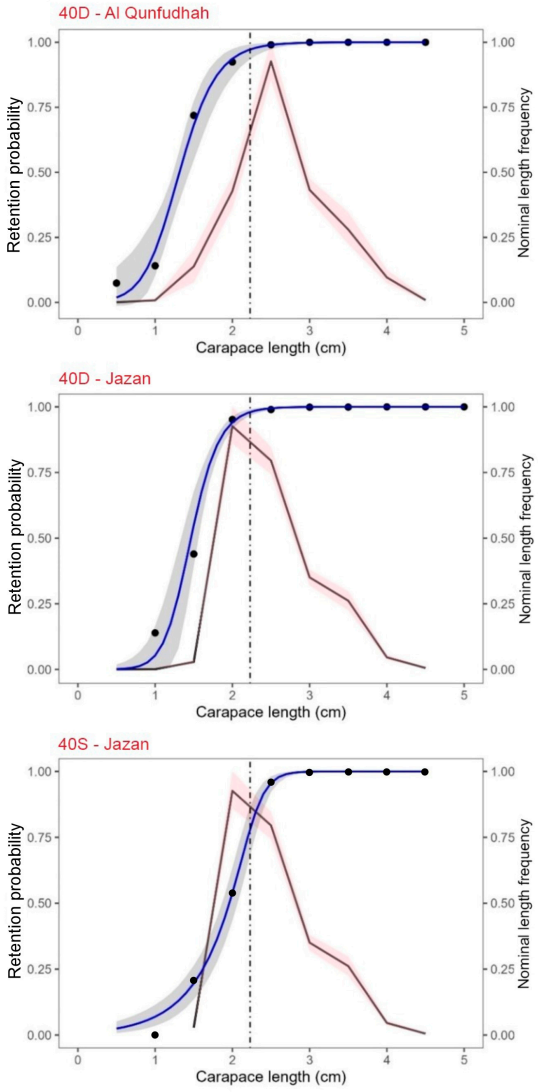


Figure 3. Selectivity curves with 95% confidence intervals for the 40D mesh codends in Al Qunfudhah and Jazan, and the 40S mesh codend in Jazan for *P. semisulcatus* (blue lines represent the selection curves, light gray areas denote the 95% CIs of the selection curves, and vertical dashed lines indicate the SMSs. Brown lines show the size distribution of the *P. semisulcatus* populations, while light pink areas represent the 95% CIs of the population size structure).

Due to the limited number of *M. monoceros* specimens caught during trawl hauls in Al Qunfudhah, selectivity results could not be obtained for this species. For the 40D mesh codend, the Richards model was identified as the best model, with the lowest *AIC* values for *M. monoceros*, and it was also the best model for the 40S codend in Jazan (Table 4). In this study, the Richards model significantly outperformed the other models in terms of low *AIC* values. The selected Richards model adequately represented the catch data for both the 40D and 40S codends, as all *p*-values were greater than 0.05 (Table 4). Most of the observation points were within the 95% CI range of the selectivity curve (Figure 4). The L_{50} and *SR* values for *M. monoceros* were estimated as 1.64 cm and 0.42 cm CL for the 40D codend and 2.04 and 0.79 cm for the 40S codend, respectively. Using a square mesh in the codend led to an increase in both the L_{50} and *SR* values for *M. monoceros* (Table 4). The estimated L_{50} values for both the 40D and 40S codends were below the SMS for *M. monoceros*.

Table 4. Summary of the *AIC* values, selectivity parameters, and fit statistics of 40D and 40S mesh codends for *M. monoceros* in Al Qunfudhah and Jazan (L_{50}: 50% retention probability; *SR*: selection range; *df:* degrees of freedom. The values in parentheses are the 95% nonparametric confidence intervals).

Codends		**40 mm Diamond**		**40 mm Square**
Locality		**Al Qunfudhah ***	**Jazan**	**Jazan**
AIC values	Logit	-	1230.27	1733.07
	Probit	-	1228.52	1730.81
	Gompertz	-	1227.96	1734.68
	Richards	-	1085.58	1725.02
Selectivity parameters	L_{50} **	-	1.64 (1.54–1.74)	2.04 (1.86–2.28)
	SR **	-	0.42 (0.31–0.54)	0.79 (0.56–1.12)
	p-value	-	0.912	0.345
	Deviance	-	0.18	3.31
	df	-	2	3

*: Could not fitted due to poor data; **: Carapace length in cm.

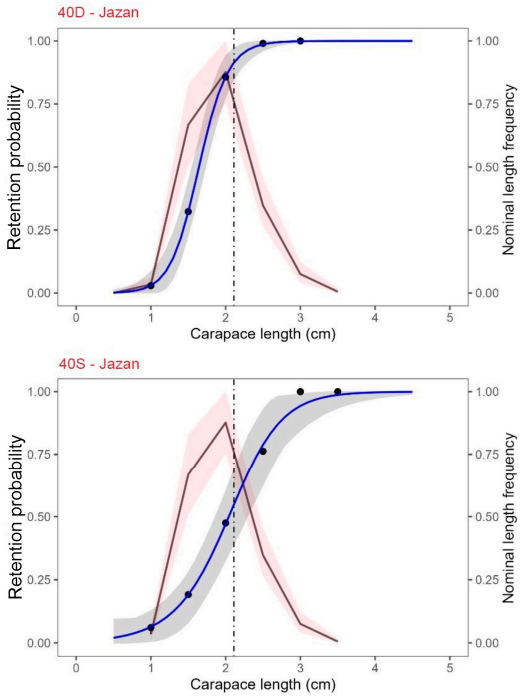


Figure 4. Selectivity curves with 95% confidence intervals for 40D and 40S mesh codends in Jazan for *M. monoceros* (blue lines: selection curves, light gray areas: 95% CIs of the selection curves, vertical dashed lines: SMSs, brown lines: size distribution of the populations of *M. monoceros* and light pink areas: 95% CIs of the population size structure).

No significant difference was found between the selectivity parameters obtained for *P. semisulcatus* in the 40D codends with similar mesh shapes and sizes, tested at different locations and dates. The differences in length-dependent retention probability for the tested codends for the two shrimp species are shown in Figure 5. The delta selectivity of the square mesh codend for both species demonstrated that the differences between the two comparisons were statistically significant and length-dependent. Most of these differences were statistically significant for shrimp within a specific length range, as the 95% CIs did not contain 0. In comparing the 40D and 40S codend for *P. semisulcatus*, the square mesh codend demonstrated a significantly lower retention probability for undersized target species in the carapace length range of 1.4–2.23 cm (Figure 5A). For *M. monoceros*, the 40S codend showed a significantly lower retention probability for undersized species in the CL range of 1.5–2.11 cm (Figure 5B).

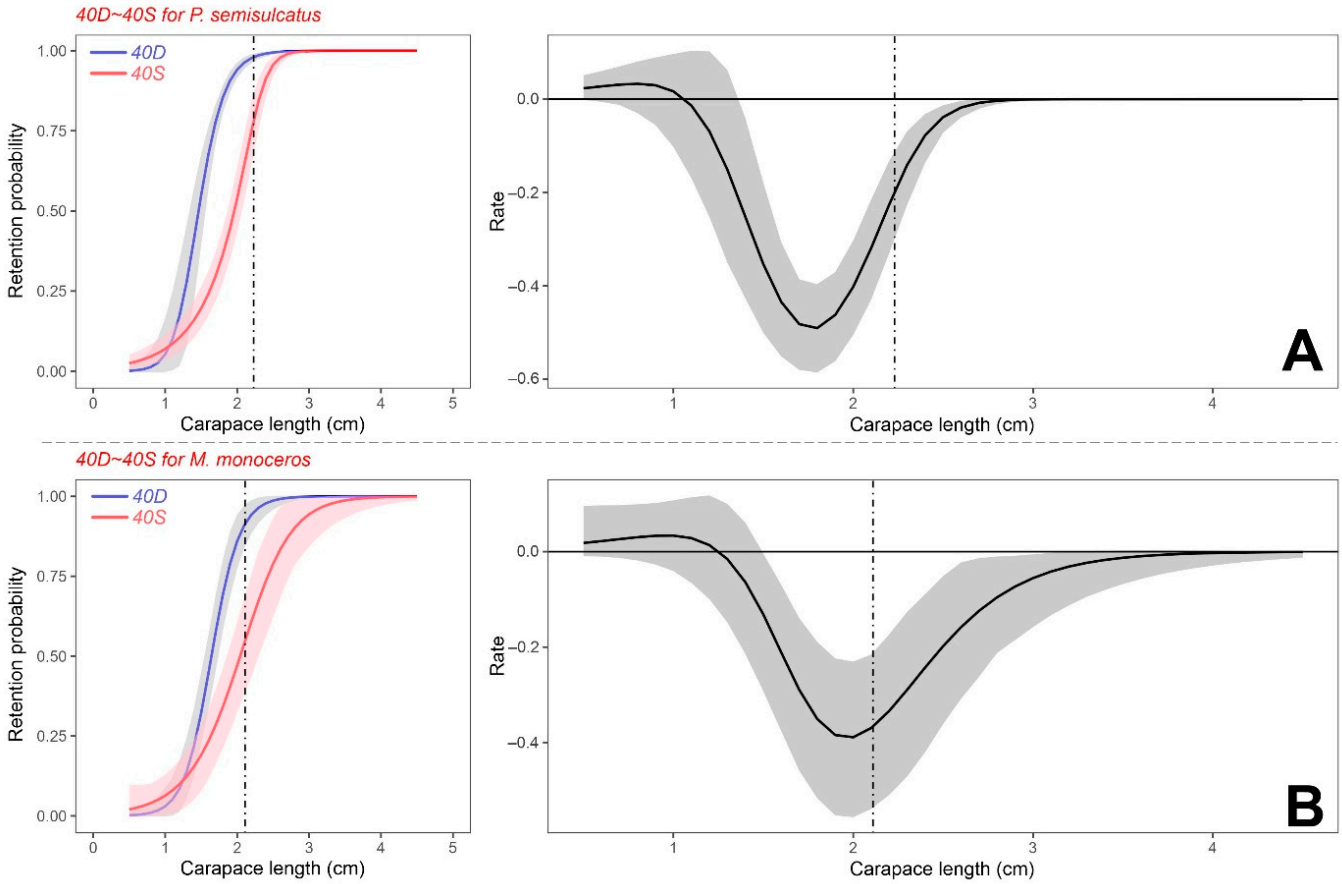


Figure 5. Delta difference curves for *P. semisulcatus* (**A**) and *M. monoceros* (**B**) in Jazan, comparing the commercially used 40D codend and the experimental 40S codend (black curves represent the fitted delta curves, dark gray areas depict the 95% CIs, and vertical dashed lines indicate the SMSs).

3.3. Fishing Efficiency

The exploitation pattern indicators revealed that catch efficiency, both for undersized (nP^-) and marketable size (nP^+) codends used for the targeted shrimp, decreased with the use of square mesh in the codend (Table 5). Using the 40S mesh instead of the 40D mesh in the codend reduced the impact on undersized individuals (nP^-) by approximately 34–40% in *P. semisulcatus* and 27% in *M. monoceros*. When evaluating the catch efficiency of the codends on shrimps above the SMS (nP^+), it was noted that the square mesh codend resulted in a reduction (economic loss) of approximately 1.8–2.1% in *P. semisulcatus* and 17% in *M. monoceros* (Table 5). However, using a square mesh net in the codend decreased the discard percentage of shrimp species caught in Jazan for both *P. semisulcatus* (11.7%) and *M. monoceros* (8.9%).

Table 5. Fishing efficiency indicators for *P. semisulcatus* and *M. monoceros* according to codend design and locality. Fishing percentage of retained specimens below (nP^-) and above (nP^+) the specific SMS and the subsequent *nDiscardRatio* (the values in parentheses indicate 95% nonparametric confidence intervals).

Species	Codend Locality	Parameters		
		***nDiscardRatio* (%)**	**nP^- (%)**	**nP^+ (%)**
P. semisulcatus	40D-AlQun	22.27 (18.05–26.20)	86.37 (77.67–91.82)	99.42 (98.43–99.91)
	40D-Jazan	37.89 (35.11–40.99)	92.87 (90.19–95.07)	99.70 (99.32–99.93)
	40S-Jazan	26.17 (21.99–30.46)	52.81 (42.51–62.47)	97.59 (95.75–98.98)
M. monoceros	40D-Jazan	69.62 (62.16–75.80)	61.42 (52.25–70.97)	98.89 (96.42–100.00)
	40S-Jazan	60.75 (50.25–70.31)	34.31 (22.16–45.22)	81.80 (67.51–94.34)

4. Discussion

This study aimed to assess the indicators of catch, size selectivity, and exploitation patterns of demersal trawls targeting shrimp species by comparing diamond and square mesh codends for the first time in the Red Sea. The catch data presented in Table 2 clearly indicate that a greater number (and consequently greater weight) of juveniles can escape from the square mesh codend, even when the mesh size remains the same. These findings are more easily comprehensible through the percentage comparisons provided at the bottom of Table 2. For all commercial shrimp and bycatch groups, except for crabs and vulnerable species such as sharks, rays, and sea turtles, the percentage of juveniles escaping from the square mesh codend is consistently higher. Interestingly, the percentage of the total weight is consistently higher than the percentage of the number of individuals for each species and bycatch group in each codend. This is because larger individuals with higher weights are retained in the codend, while those that pass through to the cover are predominantly smaller individuals. This results in a substantial increase in the number of escapements compared to those retained in the codend. Therefore, weight, depending on the number of undersized individuals escaping from the codend, is very important as a selectivity indicator.

In the present study, the bycatch rates of both the currently used diamond mesh codend (average 90.2%) in the Red Sea and the experimental square mesh (79.6%) codend were found to be quite high, which is consistent with similar studies. Mendo et al. [53] reported an 82% bycatch rate for artisanal shrimp trawl fishery in Northern Peru. Another study by Al-Baz and Chen [54] reported a bycatch ratio of 86–99% for shrimp trawling in Kuwait. Gibinkumar et al. [55] estimated an 87% bycatch rate in shrimp trawls in the coastal waters off Cochin (southwest coast of India). The mesh sizes of the codends were often between 20 and 30 mm, which resulted in high catches of immature fish and shrimp [55]. Estimates have placed the discard ratio at around 62% in China [56] and between 60 and 80% by weight in the USA [5]. The rate of discarded shrimp catches has been estimated to be around 50% in the Republic of Korea [57].

The study results unequivocally indicated that the conventional diamond mesh codends used in both Al Qunfudhah and Jazan, with a mesh size of 40 mm, exhibited low L_{50} values. These codends were ineffective at releasing undersized *P. semisulcatus* and *M. monoceros* in the Red Sea trawl fishery, which primarily targets shrimp but also captures other bycatch groups. The use of different shrimp trawls, codends, areas, and dates with the hauls conducted between 1–6 May 2023 in Al Qunfudhah and 25 May June 2023 in Jazan showed no differences in selectivity properties for *P. semisulcatus* and *M. monoceros*. However, transitioning from the diamond to the square mesh shape resulted in higher L_{50} values for both *P. semisulcatus* (34–50% increase) and *M. monoceros* (25% increase), aligning more closely with their SMSs. It is clear that the square mesh codend significantly improves the size selectivity of both shrimp species compared to the currently used diamond mesh codend. One possible explanation for these results might be that the shape of the square mesh codend better accommodates the round morphology of the shrimp species compared to the diamond mesh. With only the mesh shape changed, the square mesh codend effec-

tively releases smaller shrimp while retaining the larger ones in the codend. However, this is insufficient for the release of fish and other vulnerable species that are at risk.

In parallel with the catch and size selectivity indicators, the results of the exploitation pattern show a similar trend. The catch efficiency of codends decreases when the mesh shape is changed from diamond to square. Using the square mesh codend reduces the retention probability for undersized *P. semisulcatus* and *M. monoceros* (*nP*−), while the diamond mesh codend tends to increase it, although these differences were not significant. Compared to the conventional diamond mesh codend in the Red Sea shrimp trawl fishery, the square mesh codend successfully selected many small, undersized shrimp and fish species. Consequently, the square mesh saves labor time on deck by reducing the amount of undersized and discarded catches and also prevents damage to marketable shrimps by retaining less catch in the codend (Figure 2).

In a traditional diamond mesh codend, the mesh openings elongate under tension as the net fills with catch, causing the end meshes to clog and divert the water flow. This leads to bulging and the central meshes stretching and closing, preventing the escape of all but the smallest fish [13,58]. In contrast, the mesh openings of a square mesh codend retain the same shape as they fill with catch, allowing undersized fish to escape [7,59,60]. The *SR* values were consistently within a narrow range when only a small number of undersized individuals were selected from the diamond mesh codend. However, the *SR* value increased significantly due to the escape of a large number of individuals of all sizes from the square mesh codend.

In the Red Sea, similar to the Mediterranean Sea, the catch composition of species in trawl fisheries exhibits multi-species characteristics, showcasing a diverse array of sizes and body shapes [11,17,61–63]. Notably, numerous species in the Red Sea possess a distinctively rounded body morphology. Many studies have shown that the currently used diamond mesh codend exhibits poor selective properties for round fish species. However, the alternative square mesh codend or panel/window significantly increases size selectivity for many fish, shrimp, and cephalopod species [16,18,49,64–68]. Similarly, according to our findings, the square mesh codend also reduced the overall bycatch discard rate in the Red Sea trawl fishery.

The effectiveness of exploitation pattern indicators is directly tied to the size limitations set by MLS (recently referred to as MCRS) regulations, which are implemented to ensure the sustainability of the species. Currently, there is no established MLS or MCRS for demersal trawl fisheries targeting shrimp in Saudi Arabian waters. This absence poses a significant challenge in promoting sustainable fishing practices within shrimp harvesting areas. Implementing a legal MLS is crucial for complementing the recommendation to use square mesh codends. This additional measure is essential for promoting sustainable fishing practices in the targeted shrimp fisheries. Setting an MLS requirement aids in safeguarding juvenile shrimp, allowing them to mature and reproduce before being harvested. This, in turn, helps maintain healthy stock levels and preserves the overall ecosystem balance in the Red Sea region. Therefore, establishing a legal MLS (or MCRS) is not only relevant but imperative to ensure the long-term sustainability of shrimp fisheries in Saudi Arabia's territorial waters. It acts as a vital component in enhancing the effectiveness of exploitation pattern indicators and contributes to the overall management and conservation efforts of marine resources in the region.

Considering the overall results of our study, we suggest incorporating the use of square mesh codends in fisheries management regulations, similar to the European Union's implementation in the Mediterranean Sea, to optimize the size selectivity of marine trawl fisheries targeting shrimp species in the Red Sea. Improving the size selectivity of shrimp and fish in multi-species shrimp trawling and excluding vulnerable species can be quite challenging due to the large differences in their morphological and behavioral traits. Therefore, alternative selective devices, consisting of a combination of sorting grid/Turtle Exclusion Devices (TEDs) and square mesh panels, should be rigorously tested in Red Sea shrimp trawling to increase the selectivity of target species and reduce the discard of bycatch and vulnerable

species [69–72]. If the sorting grid is introduced in Red Sea trawling, conducting a series of experiments and thoroughly analyzing the collected data is essential. This analysis should encompass various aspects, such as selectivity, catching efficiency, survival rates, economic losses, and other relevant factors.

5. Conclusions

In this study, the selectivity of the currently used diamond mesh (40D) codends was tested for commercial shrimp species for the first time in the Red Sea in two different locations where shrimp trawling is most intense: Al Qunfudhah and Jazan. Additionally, the selectivity of a square mesh codend (40S), which is better suited to the body morphology of these shrimp species, was also investigated. The results revealed that the 40D codend had lower L_{50} values, indicating poor size selectivity for *P. semisulcatus* and *M. monoceros*, as anticipated. In contrast, the 40S codend increased the size selectivity for these species by 25% to 50%. Even though the square mesh improved the size selectivity for shrimp species, it was still insufficient when considering the SMS of these species. This study emphasizes the necessity of conducting additional research, particularly focusing on sorting grid studies for species-specific selectivity. Furthermore, there is a need to implement selective devices in these trawls, such as sorting grids to effectively separate shrimp from non-target species and TEDs to exclude vulnerable species like large rays, sharks, and sea turtles.

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