

Article

Evaluation of a Modified Codend Configuration for a Marine Mammal Bycatch Reduction Device in a Midwater Trawl Gear

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Abstract

Marine mammal Bycatch Reduction Devices (BRDs) can result in the escape of target fish species. In the present study, a modified single-layer codend configuration developed from previous studies was evaluated using BRDs with guide net angles of 30° and 45°. Catch was collected separately from the codend and the BRD cover to estimate catch loss rates and characteristics. For caught species, catch loss rates based on the number and weight of individuals were 9% and 13% for herring with the 30° guide net and 16% and 18% with the 45° guide net, respectively. For Korean pomfret, catch loss rates were 24% and 23% at 30° and 4% at 45°. These results suggest that further modification of BRD is necessary. In contrast, catch loss rates of mackerel with the 30° guide net reached 56%, whereas hairtail showed loss rates of 60% and 65% with the 45° guide net. Underwater observations indicated that catch loss was influenced by swimming behavior and entanglement with the guide net. Despite the modification of the codend to a single layer, the present study still observed high catch loss rates. However, no bycatch of marine mammals occurred during the experimental operations.

Keywords: marine mammal bycatch; bycatch reduction device; catch loss; midwater trawl; marine mammals protection act; comparability assessment

Key Contribution: This study evaluated a modified single-layer codend configuration developed from previous BRD studies. Field experiments were conducted in fishing grounds along the East and South Sea of Korea, where marine mammals are frequently observed. Although the modified configuration was evaluated under commercial fishing conditions, catch loss remained above 10%, indicating that additional modifications to the bycatch reduction device are still necessary. Across all four encounters, dolphins were observed to change direction or move away before direct interaction with the vessel or trawl gear occurred during the four opportunistic encounters.



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1. Introduction

Cetaceans, which are representative marine mammals, were once considered competitors of commercially valuable fish species consumed by humans, as they were believed

to contribute to the decline in target fish populations, thereby causing conflicts with fisheries [1]. However, previous studies have suggested that these effects are limited [2]. In addition, cetaceans are known to consume species other than those targeted by commercial fisheries, and reductions in fishery resources have been reported in ecosystems where whale populations have declined, indicative of the positive relationship between whale abundance and fishery productivity [3]. The protection and conservation of marine mammals, including cetaceans, is therefore considered necessary.

The United States has enacted and enforced the Marine Mammal Protection Act (MMPA), and various studies on reducing marine mammal bycatch have been conducted for different fisheries. In Korea, the National Institute of Fisheries Science developed bycatch reduction devices (BRDs) for trawl gear in accordance with the comparability finding standards of the U.S. National Oceanic and Atmospheric Administration (NOAA) under the MMPA [4,5].

Previous studies have primarily used acoustic deterrent devices (pingers) to reduce marine mammal bycatch [6–11]. However, concerns regarding habituation and long-term ecological impacts have prompted the development of physical BRDs for fishing gears [9,11–15]. Therefore, this study evaluated a physical BRD designed to exclude marine mammals from a midwater trawl. Several physical BRDs, including Seal Exclusion Devices (SEDs) and dolphin exclusion devices, have been developed for midwater trawl fisheries to reduce marine mammal bycatch [16,17]. These studies have primarily focused on improving the exclusion efficiency of marine mammals. However, quantitative assessments of target species catch loss and the selectivity associated with these devices remain limited.

In Korea, a series of studies have progressively developed and evaluated physical BRDs for stow nets and midwater trawl fisheries using a catch loss assessment [4,5,18,19]. For the trawl gear, marine mammal BRDs with guide nets tilted at angles of 30° and 45° were attached and tested along the East and South Sea coasts in June and September 2024 to evaluate catch loss rates for flying squid, sandfish, and hairtail, horse mackerel, mackerel, and herring by examining species-specific body characteristics and behavioral traits [4,5]. The successful exclusion of the giant jellyfish, *Nemopilema nomurai*, has also demonstrated the discharge capability of BRD for large marine organisms, including marine mammals [5].

Previous studies have demonstrated the applicability of BRDs in Korean stow net and midwater trawl fisheries using a catch loss assessment methodology [4,5]. Although these studies have confirmed the feasibility of BRDs under commercial fishing conditions, they also identified substantial catch loss in several commercially important species, indicating that further modification of the gear configuration was required.

Based on the findings of these previous studies, the codend configuration was modified from a triple-layer structure to a single-layer structure, similar to that used in commercial midwater fisheries. The present study represents the next stage of this continuing research project and evaluates the modified gear using the same experimental methodology. Specifically, this study aimed to evaluate the species catch loss and mesh selectivity of the BRD, investigate fish escape behavior using underwater observations, and identify potential gear modifications to further reduce catch loss while maintaining the performance of the BRD. The objective of this study was not to directly compare the modified codend with the triple-layer configuration, but to evaluate the performance of the modified gear using the same experimental methodology established in previous studies.

2. Materials and Methods

2.1. Test Fishing Gear with BRD

The fishing gear used in this study was the same gear as described by Jung et al. [4,5] and was employed in all experiments. Schematic diagrams of the midwater trawl gear and

the installation configuration of the BRD are shown in Figures 1 and 2, respectively. The total length of the netting, excluding the towing ropes, was 140 m, whereas the codend (hereafter referred to as the COD) measured 11.2 m in length. As shown schematically in Figure 1, the codend consisted of a single-layer net structure, with a mesh size of 120 mm. To reduce the bycatch of marine mammals, a guide net panel serving as the BRD was installed immediately ahead of the codend of the mid-water trawl gear, as illustrated in Figure 2.

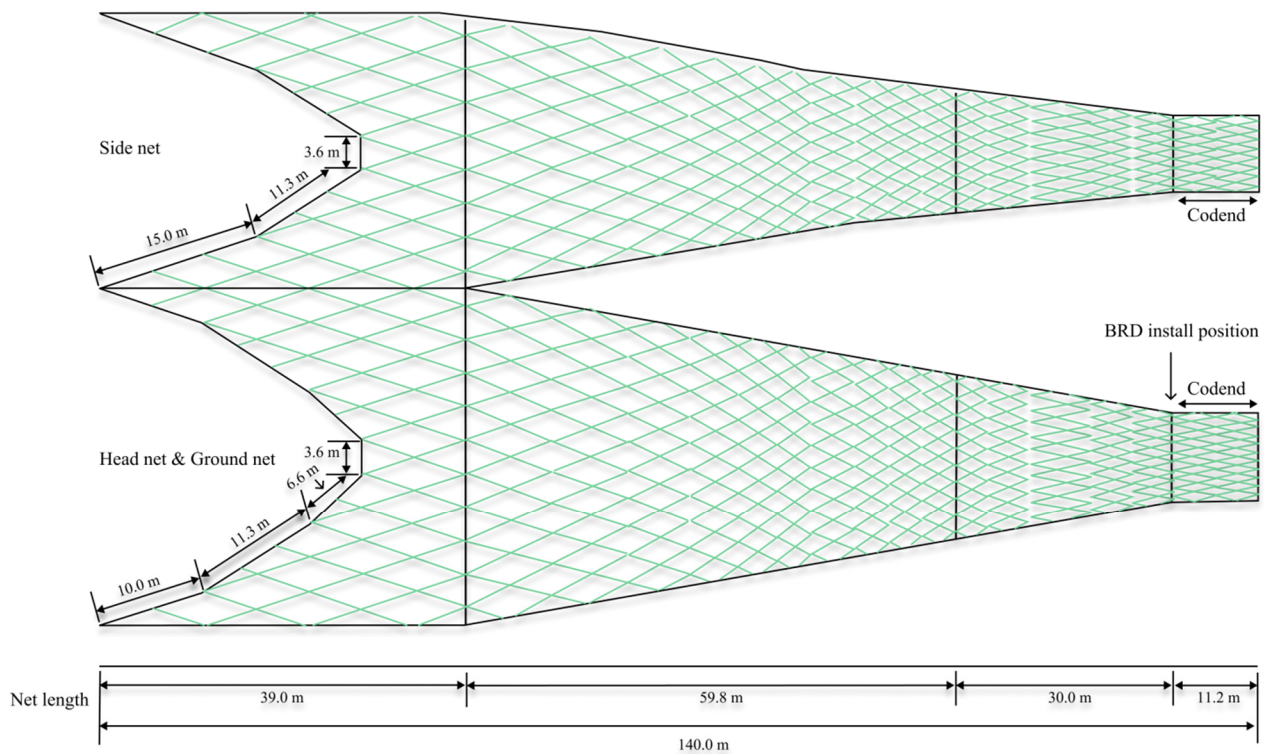


Figure 1. Design of midwater trawl used in this study.

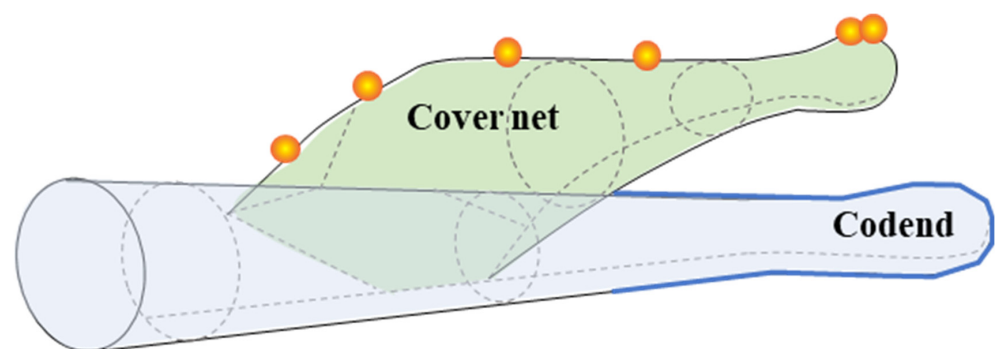


Figure 2. Revised schematic diagram of midwater trawl gear with bycatch reduction device for marine mammals.

The guide net of the BRD was constructed using polyethylene (PE) square mesh netting with a bar length of 200 mm, corresponding to a mesh perimeter of 800 mm. Two types of guide nets with tilt angles of 30° and 45° were prepared. Both guide nets had the same width of 2.0 m; however, their lengths differed according to the tilt angle, measuring 2.23 m for the 30° and 1.4 m for the 45° guide nets, respectively. Consequently, the attachment positions of the body nets differed between the two configurations. The escape opening of the BRD measured 2.0 × 1.5 m (height × width). A cover net made of PE netting with

a mesh size of 46 ± 1.4 mm (D) was attached to the escape opening in order to collect and investigate the species escaping through the BRD along the guide net.

2.2. Fishing Area

As shown in Figure 3, the fishing experiments in this study were conducted along the coasts of the South Sea [18,20] and East Sea [21,22] of Korea, where whales and dolphins are frequently observed.

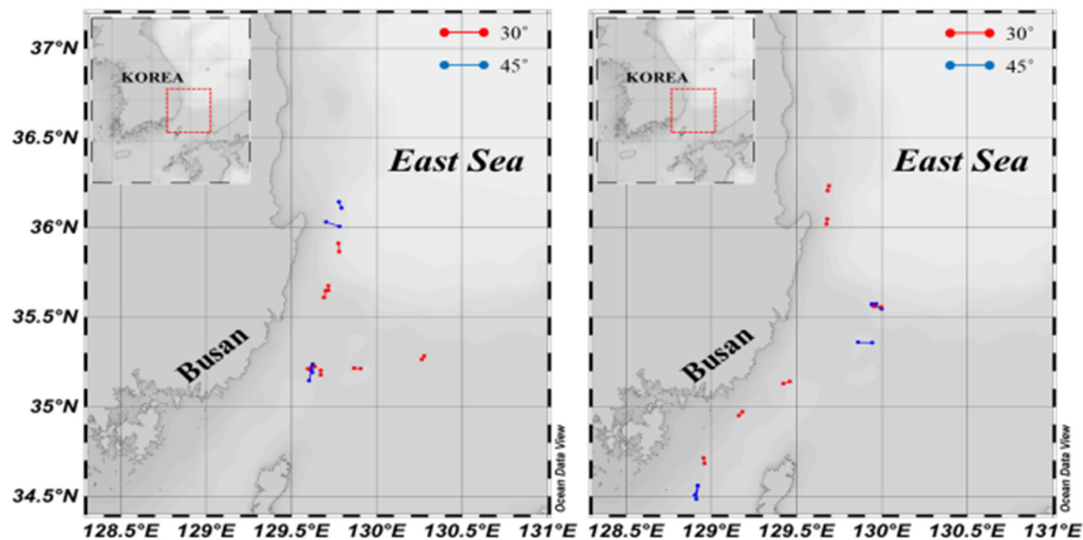


Figure 3. Map of the trawl fishing grounds (left, April; right, September).

2.3. Fishing Experiment with Test Fishing Gear with BRD

Fishing operations were conducted over 24 days and 24 hauls, with 12 operations performed between 8 April 2025 and 19 April 2025, and an additional 12 operations conducted between 8 September 2025 and 19 September 2025. The experiments were conducted using a research vessel *Tamgu-23* (1670 tons, 3474 hp) operated by the National Institute of Fisheries Science (NIFS). All fishing operations were conducted during the daytime. The towing duration for each haul was set at 1 h, with the towing speed ranging from three to five knots. The fishing experiments were conducted in waters with average depths ranging from 200 to 300 m, targeting both the surface layer (20–50 m) and the mid-water layer (100–150 m), for a total of 24 tows.

After each haul, the catch was separated into fish retained in the COD and fish that escaped through the BRD and were collected in the cover net attached to the BRD. The total length (TL) and body length (BL) of the caught species were measured and further classified by species into fork length (FL), mantle length (ML), or anal length (AL), depending on species characteristics. Length measurements to the nearest 1 mm, body weight (W) to the nearest gram, and maximum body girth (G) to the nearest 1 mm were recorded. For each haul, up to 200 individuals were randomly sampled separately from the cover net with BRD and COD catches for biological measurements. When more than 200 individuals were retained in either compartment, approximately 200 individuals were randomly selected from that compartment without regard to body size. For species analyzed in previous studies [4,5], maximum body girth was not measured for all individuals. Instead, representative individuals covering the observed body length range were selected for body girth measurements. These newly collected measurements were combined with the corresponding data from previous studies to establish species-specific body length and body girth relationships.

2.4. Investigation of the Situation of Bycatch Reduction and Catch Loss Using a Camera

To investigate the internal conditions of the fishing gear during operation, a GoPro Hero 6 underwater camera (GoPro, San Mateo, CA, USA) equipped with an LED underwater light was installed in front of the guide net, as shown in Figure 4 and Table 1, with the camera oriented toward it. The camera was positioned 1.5 m from the starting point of the net section, located immediately ahead of the COD. The camera angle was adjusted to simultaneously capture both the COD area, where the catches passed through the guide net, and the escape opening, through which organisms that failed to pass through the guide net were discharged. After each fishing operation, the underwater video footage was compared with the catch data to determine how the catches passed through the guide net and how certain individuals failed to pass through and instead escaped through the BRD escape opening.

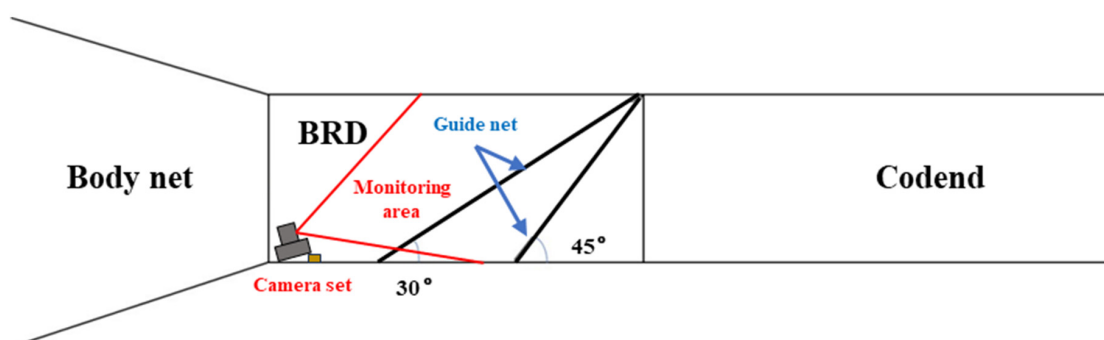


Figure 4. Position of the camera for monitoring the trawl net.

Table 1. Information on operations in experiments conducted by Tamgu-23.

Haul No.	Date	Start Position of the Haul		Tilt Angle of Guide Net
		Latitude	Longitude	
#101	9 April 2025	35°13.476' N	129°40.157' E	30°
#102	9 April 2025	35°12.829' N	129°50.713' E	30°
#103	10 April 2025	35°50.705' N	129°46.938' E	30°
#104	11 April 2025	35°16.435' N	130°16.618' E	30°
#105	11 April 2025	35°13.641' N	129°39.653' E	30°
#106	12 April 2025	35°34.920' N	129°41.251' E	30°
#107	12 April 2025	35°13.643' N	129°39.655' E	30°
#108	15 April 2025	36°09.417' N	129°46.514' E	45°
#109	15 April 2025	36°03.010' N	129°47.788' E	45°
#110	16 April 2025	35°12.264' N	129°39.960' E	45°
#111	16 April 2025	35°07.272' N	129°36.145' E	45°
#112	16 April 2025	35°10.126' N	129°37.256' E	45°
#201	9 September 2025	34°39.841' N	128°57.656' E	45°
#202	9 September 2025	34°58.996' N	129°11.542' E	45°
#203	9 September 2025	35°06.996' N	129°23.922' E	45°
#204	14 September 2025	36°15.058' N	129°41.942' E	45°
#205	14 September 2025	36°00.069' N	129°40.300' E	45°
#206	15 September 2025	35°33.585' N	129°55.604' E	45°
#207	15 September 2025	35°32.338' N	130°01.144' E	30°
#208	15 September 2025	35°32.508' N	130°01.012' E	30°
#209	16 September 2025	35°34.740' N	129°55.024' E	30°
#210	16 September 2025	35°21.451' N	129°49.924' E	30°
#211	17 September 2025	34°27.926' N	128°54.718' E	30°
#212	17 September 2025	34°28.616' N	128°54.495' E	30°

2.5. Data Analysis

In towed fishing gear, mesh selectivity may vary among fishing operations, even for the same species [23]. For example, in Mediterranean trawl fisheries, codend mesh selectivity has been shown to change significantly with variations in swimming ability caused by water temperature and increases in body girth during the spawning seasons [24,25]. Therefore, methods that estimate the average mesh selectivity across multiple fishing operations have been widely used [26–28].

In this study, as in previous studies [4,5], analyses were conducted separately for the BRD guide net with tilt angles of 30° and 45°, as well as for the pooled overall dataset. The probability that individuals of species belonging to the length class l passed through the BRD guide net and were retained in the codend, denoted by $r_c(l)$, was expressed as follows:

$$r_c(l) = \frac{n_{l2}}{n_{l1} + n_{l2}} \quad (1)$$

where n_{l1} is the number of individuals in length class l collected in the BRD section, and n_{l2} is the number of individuals in length class l retained in the codend. The representative retention probability $r(l)$ was then expressed as a function of the length class (l) and approximated using a logistic equation, according to the analytical methods described below.

$$r(l) = \frac{\exp(a + bl)}{1 + \exp(a + bl)} \quad (2)$$

where a and b are parameters of the logistic model. As described previously, mesh selectivity analyses for species interacting with the 400 mm guide net mesh of the BRD were conducted using the SELECT model based on the maximum likelihood estimation method [29–32]. Analyses were performed using R (Version 4.3.3) and the *selfisher* package (1.1.0) [33], following the procedures applied in previous studies [4,5]. The response variable consisted of the number of fish caught in the codend and the number collected in the BRD cover net for each length class. Length classes were grouped at 1 cm intervals.

The *selfisher* package estimates fishing gear selectivity using generalized linear mixed models. A logistic SELECT model was fitted using a generalized linear mixed model framework implemented in the *selfisher* package. The logistic SELECT model described the relationship between fish length and retention probability, while haul-to-haul variation was incorporated through the random effects model. The package provides both a fixed effects model, in which all haul data are combined into a single dataset by length class to estimate mesh selectivity, and a random effects model, which accounts for between haul variability caused by fishing conditions and resource availability. In the random effects model, haul was treated as the experimental unit, with haul-to-haul variation incorporated as a random effect. Bootstrap procedures were used to estimate the uncertainty associated with fitted the selectivity curves and parameter estimates. Using this analytical framework, gear selectivity was estimated separately for guide nets tilted at 30° and 45°, for the pooled guide net dataset, regardless of the tilt angle and for the codend itself.

Unlike conventional codend mesh selectivity, the present study defined selection as fish escaping through the BRD escape opening rather than fish escaping through codend meshes. Therefore, fish collected in the BRD cover net were regarded as catch loss in the subsequent analyses. The catch loss associated with BRD was estimated according to the method of previous studies [4,5,18,19], based on catches collected separately from the cover net of BRD and COD, as follows:

$$\text{Catch loss} = \frac{\text{Number of catch in BRD cover net}}{\text{Number of catch (BRD cover net + COD)}} \quad (3)$$

Catch loss was first calculated separately for each haul using Equation (3). The species-specific catch loss rate reported in this study represents the arithmetic mean of the haul-specific catch loss values.

3. Results

3.1. Composition of BL from Catch Results

The results of the 12 fishing operations conducted over 12 days in April and the 12 operations conducted over 12 days in September are summarized in Tables 2 and 3. In April, the major species caught were herring (*Clupea pallasii*), with 324 individuals weighing 12.5 kg; mackerel (*Scomber japonicus*), with 24 individuals weighing 2.6 kg; Korean pomfret (*Pampus echinogaster*), with 509 individuals weighing 97.0 kg; and hairtail (*Trichiurus lepturus*), with 30 individuals weighing 6.8 kg. A total of 892 individuals were caught during the survey period in April.

Table 2. Total catch results from 12 midwater trawl fishing operations in fishing grounds in April.

Common Name	Scientific Name	Number Caught	Weight of Catch
Hairtail	<i>Trichiurus lepturus</i>	30	6.77 kg
Korean pomfret	<i>Pampus echinogaster</i>	509	96.99 kg
Mackerel	<i>Scomber japonicus</i>	24	2.57 kg
Herring	<i>Clupea pallasii</i>	324	12.42 kg
Flying squid	<i>Todarodes pacificus</i>	5	1.08 kg
Total		892	119.82 kg

Table 3. Total catch results from each of the 12 midwater trawl fishing operations in the fishing grounds in September.

Common Name	Scientific Name	Number Caught	Weight of Catch
Hairtail	<i>Trichiurus lepturus</i>	709	86.48 kg
Blackfin flounder	<i>Glyptocephalus stelleri</i>	43	6.51 kg
Grenadier	<i>Coelorinchus japonicus</i>	12	0.32 kg
Mackerel	<i>Scomber japonicus</i>	194	70.06 kg
Herring	<i>Clupea pallasii</i>	70,699	1389.80 kg
Sailfin sandfish	<i>Arctoscopus japonicus</i>	25	1.01 kg
Flying squid	<i>Todarodes pacificus</i>	54	6.59 kg
Total		71,736	1560.77 kg

In September, the major species caught included mackerel, with 194 individuals weighing 70.1 kg; hairtail, with 709 individuals weighing 86.48 kg; flying squid (*Todarodes pacificus*), with 54 individuals weighing 6.6 kg; herring, with 70,699 individuals weighing 1389.8 kg; blackfin flounder (*Glyptocephalus stelleri*), with 43 individuals weighing 6.5 kg; sailfin sandfish (*Arctoscopus japonicus*), with 25 individuals weighing 1.0 kg; and grenadier (*Coelorinchus japonicus*), with 12 individuals weighing 0.3 kg. In total, 71,736 individuals were captured during the September.

The species composition according to BL is shown in Figure 5. Mackerels within an FL ranging from 16 to 40 cm and 21–35 cm were caught in the BRD section and the codend (COD), respectively. Hairtails within an AL range of 12–30 cm were caught in both the COD and BRD sections. Herring with an FL ranging from 9 to 23 cm and 13–16 cm were caught in the COD and the BRD section, respectively. Sandfish with a TL range of 11–18 cm and 14–17 cm were caught in the COD section and the BRD section, respectively. Pollock within a TL of 16–24 cm were caught in the COD. Flying squids within an ML range of

11–17 cm and 8–24 cm were caught in the COD section and the BRD section, respectively. Flathead flounders within a total length range of 11–29 cm and 21–30 cm were caught in the COD section and the BRD section, respectively. Korean pomfrets were caught within an FL range of 15–28 cm and 15–26 cm in the COD section and the BRD section, respectively.

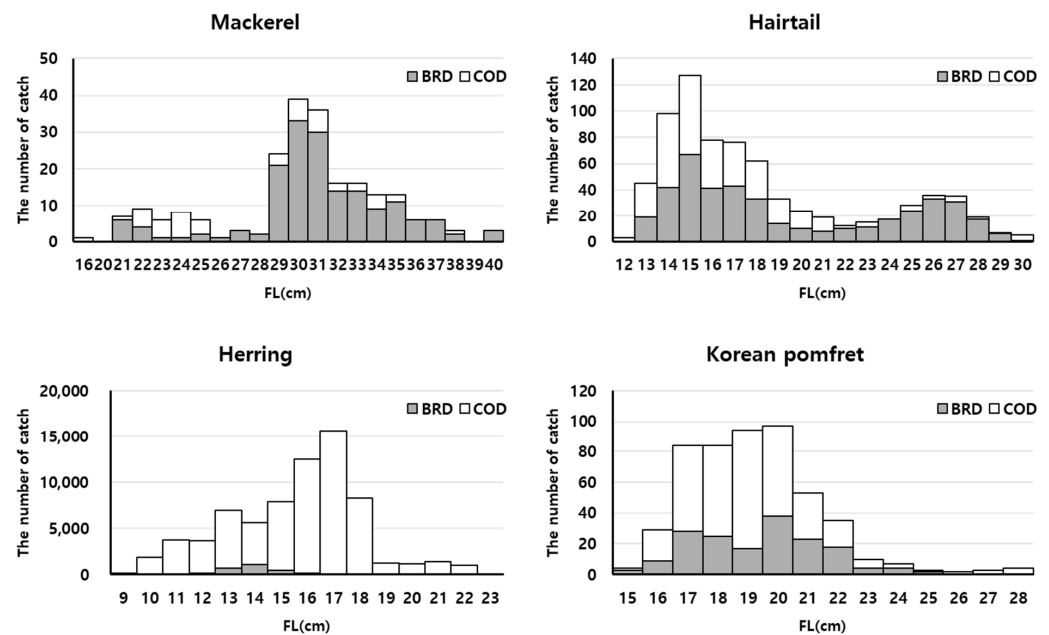


Figure 5. Body length distribution of catch by Tamgu-23. Gray bars indicate the number of fish caught in the BRD and open bars indicate the number of fish caught in the COD.

3.2. Relationship Between BL and Maximum Girth

Based on catch data, the relationships between BL and body girth (G) were estimated for herring, mackerel, and hairtail, which have been examined in previous studies [4,5], as well as for Korean pomfret, for which more than 200 individuals were newly collected in this study. The relationship is shown in Figure 6.

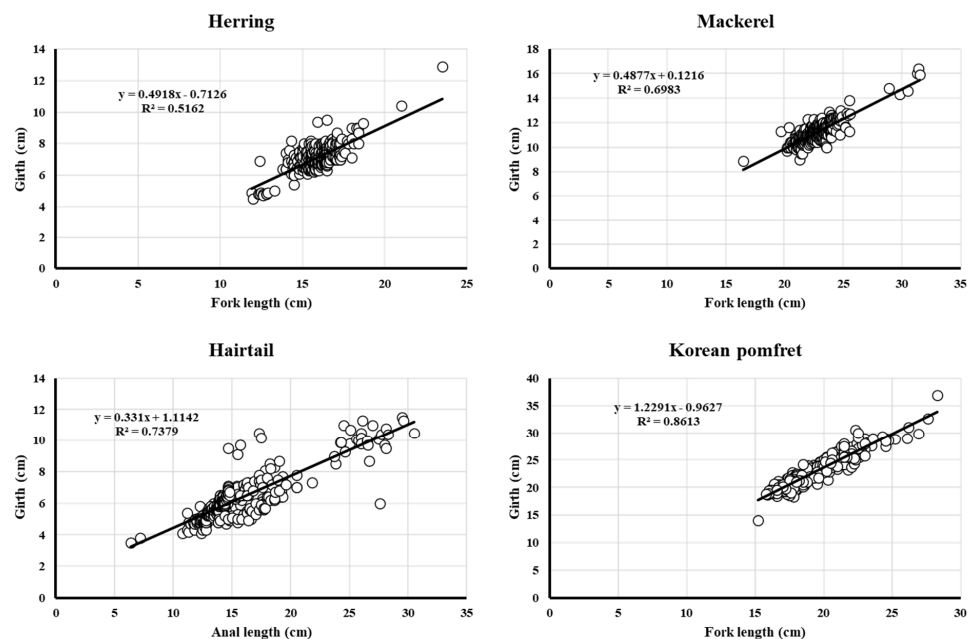


Figure 6. Relationship between body length (fork or anal length) and maximum girth in the most caught species. The solid line indicates the regression line obtained from the equation in the graph.

The relationship between fork length (FL) and body girth (G) in herring was estimated as follows:

$$G = 0.4918 \times FL - 0.7126 \quad (r = 0.72, p < 0.05, n = 431) \quad (4)$$

The relationship between fork length (FL) and body girth (G) of mackerel was estimated as follows:

$$G = 0.4877 \times FL + 0.1216 \quad (r = 0.83, p < 0.05, n = 443) \quad (5)$$

The relationship between fork length (FL) and body girth (G) for the hairtail was estimated as follows:

$$G = 0.3310 \times FL + 1.1142 \quad (r = 0.86, p < 0.05, n = 390) \quad (6)$$

The relationship between fork length (FL) and body girth (G) of Korean pomfret was estimated as follows:

$$G = 1.2291 \times FL - 0.9627 \quad (r = 0.92, p < 0.05, n = 303) \quad (7)$$

For herring, hairtail, mackerel, and Korean pomfret, BL and girth showed proportional relationships, with body girth increasing significantly as BL increased ($p < 0.05$).

3.3. Results of the Investigation on Bycatch Reduction and Catch Loss Inside the Gear

The observations of the internal gear conditions are listed in Table 4. For the BRD with a 45° guide net, 22 herring, 7 Korean pomfret, and 3 flying squid were observed over the course of 3 hauls. Among the 32 observed individuals, 19 herring, 7 Korean pomfret, and 3 flying squid entered the codend, whereas 3 herring escaped through the BRD.

Table 4. Monitoring fish inside trawl nets using the BRD.

Haul No.	Date *1	Tilt Angle of Guide Net	Remark									
			COD *2					BRD *2				
			H	HR	M	K	O	H	HR	M	K	O
#101	9 April 2025	30	32	-	-	-	1	-	-	-	-	-
#102	9 April 2025	30	3	-	-	-	1	-	-	-	-	-
#103	10 April 2025	30	-	3	-	-	-	-	1	-	-	-
#104	11 April 2025	30	5	2	-	-	1	-	1	-	-	5
#105	11 April 2025	30	-	-	-	-	-	-	-	-	-	-
#106	12 April 2025	30	-	-	-	30	-	-	-	-	30	-
#107	12 April 2025	30	-	-	-	3	1	-	-	1	-	-
#108	15 April 2025	45	-	-	-	7	1	-	-	-	-	-
#205	14 September 2025	45	-	7	-	-	1	-	1	-	-	-
#206	15 September 2025	45	-	12	-	-	1	-	2	-	-	-
#207	15 September 2025	30	-	U *	-	-	-	10	-	-	-	-
#208	15 September 2025	30	-	U *	-	-	-	21	-	-	-	-
#210	16 September 2025	30	25	-	-	-	-	U *	-	-	-	-
#211	17 September 2025	30	30	-	-	-	-	U *	-	-	-	-

*1 All observations were performed during daytime. *2, Number of observed species ("H," hairtail, "HR," herring, "M," Mackerel, "K," Korean pomfret, "O" others) were categorized by observed position (COD or BRD). U *: Uncalculated number of observations.

For BRD with a 30° guide net, 63 Korean pomfret were observed over 11 hauls. In addition, large numbers of herring and hairtail were observed, making it difficult to

accurately quantify individual counts. Most herring and hairtail entered the codend, whereas a portion of the herring and most hairtail escaped through the BRD.

In particular, hairtail frequently became entangled in the guide net in large quantities, thus blocking the guide net structure. Consequently, the escape opening was pushed downward, preventing other species from passing through the guide net and causing them to escape through the BRD opening, leading to a substantial catch loss. Such entanglement of the hairtail occurred not only in the guide net but also frequently in the body net, where larger mesh sizes were present.

3.4. Mesh Selectivity of the BRD

The mesh selectivity of the BRD was analyzed separately according to the species and BRD tilt angle. The mesh selectivity results for each species are presented according to the guide net (30° and 45° tilt angles) and pooled dataset (total), as shown in Figure 7 and Table 5.

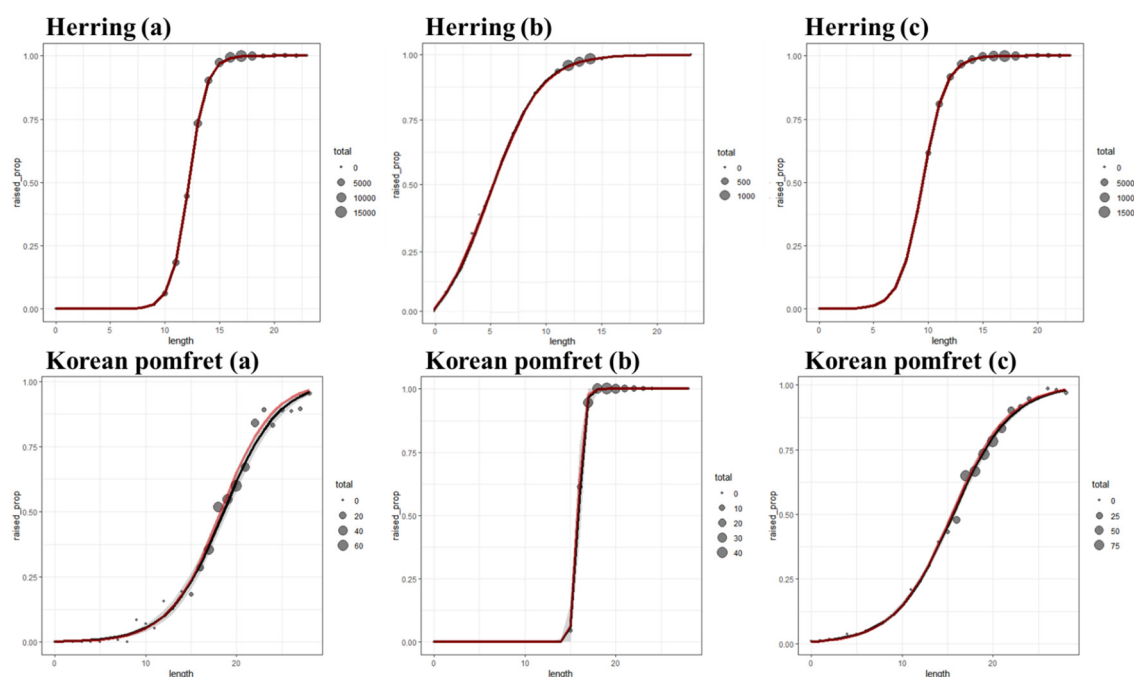


Figure 7. BRD mesh selectivity curves for species with (a) 30° BRD, (b) 45° BRD, and (c) total BRD (30° + 45°) that were caught in this study. The black line shows the selectivity curve averaged from the selectivity curve of each haul, using a random effects model. The shaded area indicates the 95% confidence range of the averaged selectivity curve, and the red line indicates the selectivity curve estimated from the pooled data for all hauls using a fixed effects model. Circles indicate the total number of fish caught by Tamgu-23.

Statistical analyses indicated that the selectivity results of herring were significant in both the fixed- and random effects models ($p < 0.05$). For the 30° guide net, the 50% selectivity length (L_{50}) was estimated at 12.2 cm in both the fixed effects and random effects models, while the selection range (S.R.) was 1.8 cm in both models. The 95% confidence interval (95% C.I.) for L_{50} was 12.1–12.3 cm, and the 95% C.I. for S.R. was 1.6–2.0 cm. For the 45° guide net, L_{50} was estimated at 5.2 cm in both models. The S.R. was estimated at 4.8 cm in the fixed effects model and 4.7 cm in the random effects model. The 95% C.I. for L_{50} ranged from 5.0 to 5.4 cm, whereas the 95% C.I. for S.R. ranged from 4.3 to 4.9 cm. For the pooled total model, regardless of the tilted angle, L_{50} was estimated at 9.5 cm in both the fixed effects and random effects models, and the S.R. was estimated at 2.3 cm in both

models. The 95% C.I. for L_{50} ranged from 8.9 to 10.1 cm, while the 95% C.I. for S.R. ranged from 1.1 to 3.5 cm.

Table 5. Estimated parameters for sorting selectivity curves after capture.

Common Name (Angle of BRD)	Estimation Method * ¹	Logistic Parameters * ²				Selectivity Curve Parameters * ³			Model Fit	
		a	b	L_{50}	C.I. of L_{50}	S.R.	C.I. of S.R.	Dev	df	p-Value
Herring (30°)	Average of each haul	−15.18 (9.41)	1.25(0.77)	12.2	12.1–12.3 cm	1.8	1.6–2.0 cm	0	22	0.02
	Sum of hauls	−15.23 (0.16)	1.25(0.01)	12.2	-	1.8	-	0	22	<0.01
Herring (45°)	Average of each haul	−2.43 (1.41)	0.46 (0.21)	5.2	5.0–5.4 cm	4.7	4.3–4.9 cm	0	22	0.02
	Sum of hauls	−2.39 (1.16)	0.46 (0.09)	5.2	-	4.8	-	0	22	<0.01
Herring (Total)	Average of each haul	−9.08 (5.00)	0.96 (0.52)	9.5	8.9–10.1 cm	2.3	1.1–3.5 cm	0	22	<0.05
	Sum of hauls	−9.07 (0.18)	0.96 (0.02)	9.5	-	2.3	-	0	22	<0.01
Korean pomfret (30°)	Average of each haul	−6.20 (2.29)	0.33 (0.12)	18.5	18.2–18.9 cm	6.6	5.7–7.0 cm	0	27	<0.01
	Sum of hauls	−6.41 (1.18)	0.35 (0.06)	18.3	-	6.3	-	0.1	27	<0.01
Korean pomfret (45°)	Average of each haul	−49.11 (49.11)	3.09 (3.10)	15.9	15.8–16.0 cm	0.7	0.5–0.9 cm	0	27	0.03
	Sum of hauls	−51.51 (18.84)	3.26 (1.16)	15.8	-	0.7	-	0.1	27	<0.01
Korean pomfret (Total)	Average of each haul	−4.89 (1.78)	0.31 (0.11)	15.6	15.4–15.6 cm	7.0	6.8–7.2 cm	0	27	<0.01
	Sum of hauls	−4.96 (1.13)	0.32 (0.06)	15.5	-	6.9	-	0.1	27	<0.01
Mackerel (30°)	Average of each haul	−1.523 (0.799)	0.003 (0.034)	Error	Error	Error	Error	0	39	0.99
	Sum of hauls	−1.488 (1.377)	0.001 (0.046)	Error	-	Error	-	0	39	0.99
Hairtail (45°)	Average of each haul	−0.25 (0.71)	−0.003 (0.04)	Error	Error	Error	Error	0	29	0.98
	Sum of hauls	−0.29 (0.30)	0.001 (0.01)	Error	-	Error	-	0	29	0.92

*¹ Average of each haul; parameters were estimated using a random effects model for each haul, and the average values are shown. The sum of the haul parameters was estimated from the catch results summed from all hauls using a fixed model. *² Parameters for Equation (2). Values in parentheses are standard errors. *³ C.I., 95% confidence interval; the value of C.I. (95% confidence interval) of L_{50} and C.I. could not be estimated.

Statistical analyses of Korean pomfret showed significant selectivity in both the fixed- and random effects models ($p < 0.05$). For the 30° guide net, L_{50} was estimated at 18.3 cm in the fixed effects model and 18.6 cm in the random effects model. The S.R. values were 6.3 cm and 6.6 cm, respectively. The 95% C.I. for L_{50} ranged from 18.2 to 18.9 cm, whereas the 95% C.I. for S.R. ranged from 5.7 to 7.0 cm. For the 45° guide net, L_{50} was estimated at 15.8 cm in the fixed effects model and 15.9 cm in the random effects model. The S.R. was 0.7 cm for both models. The 95% C.I. for L_{50} ranged from 15.8 to 16.0 cm, and the 95% C.I. for S.R. ranged from 0.5 to 0.9 cm. For the pooled total model, regardless of the tilted angle, L_{50} was estimated at 15.6 cm in the fixed effects model and 15.5 cm in the random effects model, while the S.R. values were 6.9 cm and 7.0 cm. The 95% C.I. for L_{50} ranged from 15.4 to 15.6 cm, whereas the 95% C.I. for S.R. ranged from 6.8 to 7.2 cm.

However, the statistical analyses for both mackerel and hairtail did not show significant selectivity in either the fixed- or random effects models ($p > 0.05$). For both species, the retention probabilities did not exceed 0.5 across the observed length ranges. Most of the measured mackerel exhibited estimated retention probabilities below 0.2. As a result, both L_{50} and S.R. values fell outside the observed length ranges, and a reliable estimation of the 95% confidence intervals for L_{50} and S.R. was not possible.

3.5. Results of Catch Loss Rate by the BRD

The species-specific catch loss rates associated with the installation of the BRD are presented in Table 6. For herring, the catch loss rates based on the number of individuals were 9% at 30° and 16% at 45°. Based on the catch weight, the corresponding loss rates were 13% and 18% for the 30° and 45° guide nets, respectively. For Korean pomfret, catch loss rates based on the number of individuals were 24% at 30° and 4% at 45°. Based on the catch weight, the corresponding loss rates were 23% and 4% for the 30° and 45° guide nets, respectively. Mackerel and hairtail caught under the 30° and 45° guide nets exhibited substantially higher catch-loss rates. Based on the number of individuals, mackerel had a catch loss rate of 56% at 30°, whereas hairtail had a catch loss rate of 60% at 45°. Based on catch weight, the corresponding loss rates were 56% for mackerel and 65% for hairtail.

Table 6. Catch loss rate of species by tilt angle.

Name	Scientific Name	Catch Loss Rate (%)					
		30°		45°		Total (Average)	
		N *	W *	N *	W *	N *	W *
Herring	<i>Clupea pallasii</i>	9	13	16	18	13	16
Korean pomfret	<i>Maurolucus muelleri</i>	24	23	4	4	14	14
Mackerel	<i>Scomber japonicus</i>	56	56	-	-	56	56
Hairtail	<i>Trichiurus lepturus</i>	-	-	60	65	60	65

N * indicates catch loss rates based on the number of individuals. W * indicates catch loss rates based on the catch weight.

Comparisons among tilt angles indicated that the 30° angle produced lower catch loss rates for herring than the 45° angle, suggesting a better performance for this species. In contrast, 45° resulted in lower catch loss rates for Korean pomfret than 30°, indicating superior performance for this species. Significant differences in catch loss rates according to tilt angle were observed for both the number and weight of catches ($p < 0.05$). In contrast, mackerel caught only at a 30° angle and hairtail caught only at a 45° angle exhibited catch loss rates exceeding 50%, indicating that neither tilt angle resulted in satisfactory retention performance for these species.

3.6. Opportunistic Observations of Marine Mammals During Trawl Field Operations

The occurrence of marine mammals before fishing is shown in Figure 8 and Table 7. Within the fishing grounds of the East Sea, marine mammals were observed on four occasions during the two years of trawl operations (2024–2025). The 2024 records were obtained during previous field trials [4,5] and were included here as supplementary field observations. These encounters were recorded opportunistically by researchers aboard the vessel rather than through a standardized marine mammal observation protocol. No incidental bycatch of marine mammals occurred during any of the fishing operations.

Table 7. Occurrence of dolphins during the total trawl operations (2024–2025).

Observed Date	Interaction with Gear	Bycatch
13 June 2024.	Moved from the side depending on the towing direction with faster swimming speed	-
5 September 2024.	Appeared in front of vessel and moved toward the gear, but divided into two groups and evaded the vessel and gear	-
9 September 2024.	When the operation ended, moved forward to the gear but evaded near the gear	-
10 April 2025.	Appeared before the operation but disappeared during the operation	-



Figure 8. Mass appearance of dolphins immediately before trawl operation.

4. Discussion

In the present study, the codend mesh size was expanded to 120 mm, which was more than twice the legally permitted mesh size of 55 mm currently used in commercial trawl codends in Korea [34]. The fishing gear used in previous studies was originally designed for resource surveys associated with the Total Allowable Catch (TAC) management system; therefore, the codend mesh size was intentionally designed to be very small to improve resource estimation accuracy [4,5]. However, this design may restrict the internal water flow within the codend [35]. Therefore, the codend mesh size was increased to 120 mm, and the modified gear was evaluated under commercial fishing conditions. Mesh selectivity was quantitatively estimated using the covered BRD method, whereas underwater camera observations were used only to interpret fish behavior around the guide net and escape opening. The objectives of this study were to evaluate species-specific mesh selectivity and catch loss associated with the modified BRD configuration and to identify potential gear modifications that could reduce catch loss while maintaining the intended function of the BRD.

The major species caught in this study, including herring, Korean pomfret, mackerel, and hairtail, are commercially important and widely consumed fish species in Korea [36–39]. Among these, hairtail and mackerel are designated as target species under the TAC management system, and TAC regulations are particularly applicable to trawl fisheries that target hairtail [37]. Korean pomfret is an important species widely produced and consumed in Korea [39,40].

4.1. Efficiency of the Bycatch Reduction Device

The selectivity characteristics of the BRD were analyzed according to the tilt angle, mesh selectivity, fish schooling behavior, and biological characteristics of the species. In this study, the marine mammal BRD consisted of a guide net with a mesh size of 400 mm and guide net tilt angles of 30° and 45°, installed in the section immediately ahead of the codend.

4.1.1. Selectivity According to the Tilted Angle of the BRD

From the perspective of the tilt angle of guide net selectivity, catch loss rates for herring and Korean pomfret were compared according to the number and weight of catches. Mackerel and hairtail were observed under only one guide net configuration each and were therefore evaluated descriptively without comparisons between tilt angles. Herring resulted in lower catch loss rates at 30° than at 45°, suggesting that a 30° guide net is more appropriate for this species. In contrast, Korean pomfret showed lower catch loss rates at 45° than at 30°, indicating that the 45° guide net may be more suitable for this species.

However, compared to herring, relatively few Korean pomfrets were caught, and the enlarged codend mesh may have allowed some individuals to escape through the codend meshes. The body girth of Korean pomfret ranged from 14.1 to 36.9 cm, which was smaller than the codend mesh perimeter of 800 mm, suggesting that escape through the codend meshes was physically possible. Previous studies on body girth and codend mesh selectivity have reported that fish can pass through meshes when the maximum body girth is smaller than the mesh perimeter [41,42].

Camera observations confirmed that 40 Korean pomfret were observed under the 30° guide net, whereas only 10 were observed under the 45° guide net. Similarly, catch data showed that 438 Korean pomfret were caught using a 30° guide net, whereas only 71 individuals were caught using a 45° guide net. These results suggest that the poorer retention performance observed with the 30° guide net may have resulted from Korean pomfret escaping through the codend meshes after entering the codend. In addition, the relatively small number of Korean pomfret caught under the 45° guide net may have contributed to the lower estimated catch-loss rates. Another possible explanation is related to the body morphology of Korean pomfret. Because the Korean pomfret possesses a relatively deep body shape, the projected mesh opening area of the 30° guide net may have been too small to allow passage, whereas the 45° guide net provided a larger projected opening area, allowing more individuals to pass through the guide net and enter the codend.

In contrast, herring were caught in extremely large quantities, and the codend became densely packed with fish, effectively blocking the codend mesh and preventing escape. Although the body girth of the herring was smaller than that of the Korean pomfret and theoretically allowed passage through the codend mesh, observations during hauling showed that catches exceeding 10,000 individuals completely blocked the codend meshes, making escape practically impossible. Meanwhile, the mackerel and hairtail could not be compared directly between tilt angles because they were captured only in a single configuration. Nevertheless, previous studies have reported substantial catch losses for both these species when a BRD is used [4,5].

Verification using underwater camera footage showed that, as observed in previous studies, the guide net with a 30° guide net maintained a more stable and fully expanded configuration than the 45° guide net [4,5]. Previous studies suggested that this phenomenon results from a triple-layer codend structure. However, even after replacing the codend with a single-layer structure and increasing the mesh size, the overall deployment pattern of the guide net remained similar. Under the 30° guide net, a relatively loose and stable structure is maintained, providing sufficient internal space within the trawl gear. In contrast, under the 45° guide net, the guide net could not expand properly and instead experienced strong hydrodynamic resistance, causing the BRD section to constrict into the surrounding body net. Consequently, the water flow inside the codend became unstable, and the escape opening was pushed downward, causing large quantities of fish to escape through the BRD instead of entering the COD. Therefore, despite modifications in the net structure, the present results support previous findings [4,5] indicating that the 30° guide net provides

a more effective configuration than the steeper 45° guide net. However, for mackerel and hairtail, the large catch losses observed in this study were likely influenced by species-specific behavioral and morphological characteristics unrelated to tilt angle.

4.1.2. Selectivity According to the Mesh Size of the Bycatch Reduction Device

From the perspective of mesh selectivity, the relationships between body girth and mesh perimeter of the BRD (800 mm) were examined for herring, Korean pomfret, mackerel, and hairtail. Across the entire body-length range caught in this study, body girth (G) ranged from 4.5 to 12.9 cm for herring, 14.1–36.9 cm for Korean pomfret, 8.9–16.4 cm for mackerel, and 3.5–11.5 cm for hairtail. The ratios between the body girth and mesh perimeter ranged from 0.04 to 0.46. Although the body girths of all species were substantially smaller than the mesh perimeter, considerable catch loss still occurred through selection by BRD. These findings suggest that factors such as the projected opening area of the mesh determined by the tilted angle and species-specific schooling behavior had greater effects on selectivity than the absolute mesh size itself.

Previous selectivity studies conducted in the Baltic Sea have similarly reported that selectivity is influenced not only by mesh size, but also by net geometry and hanging ratio [28,43]. Previous studies have documented substantial catch losses even when the body girth is considerably smaller than the mesh perimeter [4,5]. Similar patterns were observed in the present study, indicating that mesh size had a relatively smaller influence on selectivity than tilt angle and behavioral characteristics.

4.1.3. Selectivity According to Schooling Behavior and Biological Characteristics

Because catch loss occurred despite body girths being markedly smaller than the mesh perimeter, selectivity was considered to be more strongly influenced by species-specific behavioral and biological characteristics than by mesh selectivity alone.

Artificial lighting was used to improve image quality during underwater observations. Although artificial illumination may influence the behavior of some fish species, the camera was used primarily to qualitatively identify escape routes and interactions with the guide net rather than to quantify detailed behavioral responses. Therefore, the underwater observations were interpreted as supporting evidence for the catch data, and BRD escape opening rather than as an independent behavioral experiment.

Herring are classified as a migratory pelagic fish and are known to exhibit rapid swimming behavior [44]. In previous camera observations, herring were observed to continuously swim in front of the guide net and, after becoming fatigued, eventually pass through the BRD and enter the codend [5]. In addition, even larger herring individuals remained relatively small compared with the mesh size. Similar to previous studies, herring located in the upper portion of the fish school could pass through the upper section of the guide net and enter the codend successfully, resulting in relatively low catch loss rates.

In contrast, relatively little information is available on the behavioral characteristics of Korean pomfret beyond body morphology and feeding ecology [40,45,46]. However, underwater camera observations showed that the Korean pomfret either escaped through the guide net or entered the codend. These behavioral observations are consistent with the quantitative selectivity results obtained using the covered BRD method and suggest that the projected opening area of the guide net meshes may influence the escape behavior of Korean pomfret. Therefore, adjusting the tilt angle may improve selectivity. However, because the codend mesh size in this study was relatively large, and the catch quantity of Korean pomfret under the 45° configuration was limited, further observations are required to evaluate the effect of the projected mesh opening area more accurately. Future studies should investigate the selective characteristics of Korean pomfret in greater detail.

Behavioral studies on hairtail in handline and longline fisheries have shown that this species exhibits vertical migration behavior [47]. Acoustic surveys have also reported that the daytime swimming layer of the hairtail is deeper than its nighttime swimming layer [48]. Previous studies have suggested that the high catch loss rates observed for hairtail are associated with their vertical swimming behavior and deeper swimming distribution, which causes most hairtail schools to enter the trawl gear and remain in the upper portion of the net. Camera observations have confirmed that hairtail frequently escape directly through the upper BRD opening, leading to substantial catch loss [5]. However, the present study also revealed that the elongated body shape of hairtail plays an important role in selectivity. Individual hairtail that did not contact the guide net could pass into the codend, whereas individuals that contacted the guide net were often wrapped around the meshes and remained trapped, as shown in Figure 9. These findings indicate that the biological characteristics of the hairtail, particularly body shape and swimming behavior, are among the most important factors influencing selectivity.

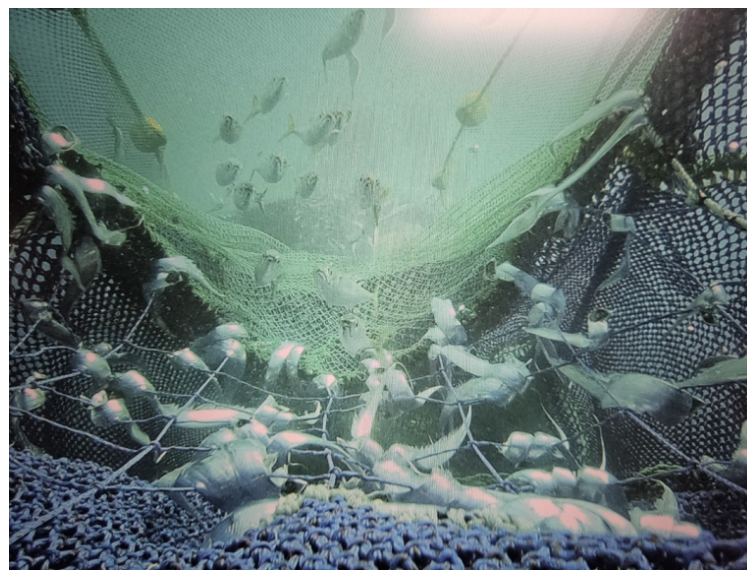


Figure 9. Hairtail entangled in the BRD guide net during towing.

Although mackerel are migratory pelagic fish characterized by rapid swimming behavior similar to that of herring [43,49,50], catch loss rates exceeded 50%, indicating that most individuals failed to pass through the BRD and instead escaped through the escape opening. Mackerels are known to form large schools, possess larger body sizes than herrings, and swim at relatively high speeds [49,50]. Camera observations in this study showed that, unlike herring, fatigued mackerel frequently lost equilibrium and overturned while approaching the guide net. Owing to their relatively large body size, these individuals were unable to pass through the guide net meshes and instead collided with the BRD structure before escaping through the escape opening. Similar phenomena have been reported in previous studies [5]. These findings suggest that enlarging the guide net mesh size may be necessary to improve the retention performance of mackerel. In addition, the installation of an upper-panel structure that redirects escaping fish downward within the trawl gear may help guide individuals toward the lower section of the guide net and subsequently into the codend, thereby reducing catch loss.

4.2. Catch Loss and Possible Modification Measures

This study examined catch loss in target species associated with the installation of a marine mammal bycatch reduction device (BRD). Previous studies have reported catch

loss rates exceeding 10% [4,5]. In the present study, herring exhibited a catch loss rate of 9% based on the number of individuals in the 30° tilted configuration, whereas Korean pomfret showed a catch loss rate of 4% in the 45° configuration, regardless of whether catch number or catch weight was considered. Under all other conditions, the catch loss rates for herring and Korean pomfret exceeded 10%, whereas hairtail and mackerel showed catch loss rates exceeding 50%. Previous trawl selectivity experiments reported that the installation of a cover net around the codend reduces water flow and alters selectivity characteristics [51]. Accordingly, the triple-layer codend used in previous studies was replaced with a single-layer codend in the present study. However, despite this modification, substantial catch losses still occurred, indicating that additional modifications are required. The possible solutions can be categorized into three approaches:

- (i) First, an enlargement of the guide net mesh size is necessary. As observed in the present study, species such as herring and jack mackerel could pass through the guide net meshes even after becoming fatigued and overturning because their body sizes remained within the mesh-opening range. In contrast, the body size of the mackerel exceeded the effective mesh opening size, which prevented individuals from passing through the guide net. Therefore, future studies should redesign the guide net by enlarging the mesh size while maintaining sufficiently small openings to prevent the passage of marine mammals. Additional experiments are required to determine the optimal mesh size. However, the enlargement of guide net meshes may also increase the possibility of dolphins entering the codend. Careful consideration of their effects on other species is required before the implementation of larger mesh sizes.
- (ii) Second, when the escape opening sinks downward and allows a large number of fish to approach the upper part of the trawl gear, buoyancy should be added to maintain the escape opening in an elevated position, thereby guiding the fish toward the codend through the guide net. Such buoyancy can be provided either by attaching floats to the section where the escape opening and guide net connect, or by installing kites that lift the escape opening upward. As kites generate a greater lift force as the towing speed increases, they may be more effective than floats during high-speed towing [52].

In addition, the installation of an upper-panel structure around the escape opening may help redirect fish that fail to pass through the guide net back toward the lower section of the trawl gear, thereby reducing escape through the BRD. Reducing the size of escape openings may also help decrease catch loss. In Australia, such an upper-panel system has been termed a Seal Exclusion Device (SED), which was developed to reduce marine mammal bycatch while minimizing catch loss in target species such as mackerel [16,17]. Previous studies have reported that this method successfully released seals without causing mortality and may also be suitable for reducing dolphin bycatch [16]. Furthermore, the BRD used in this study employed a relatively large escape opening measuring 2×1.5 m, which may have contributed substantially to catch loss. As an alternative approach, elastic escape openings similar to those used in stow-net BRDs [18,19] may help reduce catch loss while allowing marine mammals to escape effectively. Future studies in Korea should evaluate the applicability of flexible escape opening systems.

- (iii) Third, the use of a funnel guide panel structure may help reduce catch loss while maintaining the ability to release marine mammals effectively. This method has been applied not only in midwater trawl fisheries overseas [53] but also in Korean stow-net fisheries [18,19], where it has been used successfully to release finless porpoises while maintaining catch loss rates below 5% for the target species. However, in trawl fisheries, funnel guide net systems are associated with operational disadvantages because their maintenance and handling are relatively difficult. Moreover, few studies have evaluated the effectiveness of tongue-grid systems specifically for reducing

marine mammal bycatch in trawl fisheries. Therefore, the introduction of BRDs with funnel guide nets into trawl fisheries should be approached with caution and evaluated through additional experimental studies.

4.3. Possibility of Whale Entry into Trawl Gear

In the studies conducted thus far, dolphins were occasionally observed before trawl operations began. However, once the towing operations began, the dolphins separated and moved away from the towing path, and no cases of marine mammal bycatch were recorded. Additionally, studies on the acoustic characteristics of finless porpoises have reported that vessel noise can alter the behavior of these animals [54]. According to the U.S. MMPA comparability assessment [55], marine mammal bycatch incidents associated with trawl fisheries were recorded between 2014 and 2017, resulting in non-compliance with the assessment criteria during that period. However, no bycatch incidents were reported in 2018. In the present study, marine mammals observed near fishing grounds swam away at speeds faster than the towing speed during fishing operations, and no bycatch events occurred.

Previous studies reported that dolphins exhibit an average swimming speed of approximately 1.5 m/s and a maximum sustainable swimming speed of approximately 11.5 m/s, which exceeds the average towing speed of 3–5 knots (1.5–2.6 m/s) used in the present trawl operations [56]. In addition, the behavioral responses of dolphins to vessel engine noise have been previously documented [57]. These findings suggest that both vessel engine noise and hydrodynamic noise generated during trawl towing may function as deterrent factors that discourage marine mammals from approaching the fishing gear. However, these observations were experienced briefly and were not encountered during every fishing operation. Therefore, further studies are required to verify its consistency and better understand the underlying mechanisms.

5. Conclusions

Overall, previous studies [4,5] demonstrated that the marine mammal bycatch reduction device developed in this study was capable of effectively excluding large jellyfish species, suggesting that the device may also achieve near-complete exclusion of marine mammals from trawl gear. However, the installation of the BRD inevitably results in the catch loss of commercially important target species, which may raise concerns among fishers regarding its practical application in commercial fisheries. Therefore, to improve applicability in commercial midwater trawl fisheries, the guide net mesh size tested in the present study should be enlarged appropriately, while additional devices, such as upper-panel systems similar to SEDs [50,51], buoyant floats, or kites, should be incorporated to reduce catch loss.

Furthermore, funnel guide net systems should be considered as a potential method for substantially reducing catch loss while maintaining effective marine mammal exclusion performance. In such cases, improvements in maintenance and operational handling are necessary to facilitate their practical use in trawl fisheries. Therefore, future studies should focus on further modification of the BRD to reduce catch loss in target species while maintaining effective marine mammal exclusion performance. In addition, further research is needed to better understand the behavioral responses of marine mammals to trawl fishing operations, particularly with respect to attraction, avoidance, and interaction with active fishing gear.

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Institutional Review Board Statement: This study used a marine mammal bycatch reduction device but did not catch marine mammals.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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References

1. Lavigne, D.M. Marine mammals and fisheries: The role of science in the culling debate. In *Marine Mammals: Fisheries, Tourism, and Management Issues*; Gales, N., Hindell, M., Kirkwood, R., Eds.; CSIRO: Melbourne, Australia, 2003.
2. Roman, J.; Estes, J.A.; Morissette, L.; Smith, C.; Costa, D.; McCarthy, J.; Nation, J.B.; Nicol, S.; Pershing, A.; Smetacek, V. Whales as marine ecosystem engineers. *Front. Ecol. Environ.* **2014**, *12*, 377–385. [\[CrossRef\]](#)
3. Morissette, L.; Christensen, V.; Pauly, D. Marine mammal impacts in exploited ecosystems: Would large scale culling benefit fisheries? *PLoS ONE* **2012**, *7*, e43966. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Jung, J.M.; Park, M.S.; Choi, K.S. A study on the catch losses and mesh selectivity related to the attachment of marine mammal bycatch reduction devices on midwater trawl gear. *Fishes* **2024**, *9*, 391. [\[CrossRef\]](#)
5. Jung, J.M.; Kim, H.Y.; Cha, B.J.; Kim, S.J.; Kim, T.S.; Hyun, G.C.; Choi, K.S. Catch losses and reduction of bycatch for jellyfish using marine mammal bycatch reduction devices in midwater trawl gear. *Fishes* **2025**, *10*, 276. [\[CrossRef\]](#)
6. Leeney, R.H.; Berrow, S.; McGrath, D.; O'Brien, J.; Cosgrove, R.; Godley, B.J. Effects of pingers on the behaviour of bottlenose dolphins. *J. Mar. Biol. Assoc. U. K.* **2007**, *87*, 129–133. [\[CrossRef\]](#)
7. Brotons, J.M.; Munilla, Z.; Grau, A.M.; Rendell, L. Do pingers reduce interactions between bottlenose dolphins and nets around the Balearic Islands? *Endanger. Species Res.* **2008**, *5*, 301–308. [\[CrossRef\]](#)
8. Gazo, M.; Gonzalvo, J.; Aguilar, A. Pingers as deterrents of bottlenose dolphins interacting with trammel nets. *Fish. Res.* **2008**, *92*, 70–75. [\[CrossRef\]](#)
9. Buscaino, G.; Buffa, G.; Sarà, G.; Bellante, A.; Tonello, A.J.; Hardt, F.A.S.; Cremer, M.J.; Bonanno, A.; Cuttitta, A.; Mazzola, S. Pinger affects fish catch efficiency and damage to bottom gill nets related to bottlenose dolphins. *Fish. Sci.* **2009**, *75*, 537–544. [\[CrossRef\]](#)
10. Gönener, S.; Özsandıkçı, U. Technical measures in order to decrease interactions between dolphins and fishermen: Pingers. *J. Aquac. Eng. Fish. Res.* **2017**, *3*, 151–159. [\[CrossRef\]](#)
11. Buscaino, G.; Ceraulo, M.; Alonge, G.; Pace, D.S.; Grammauta, R.; Maccarrone, V.; Bonanno, A.; Mazzola, S.; Papale, E. Artisanal fishing, dolphins, and interactive pinger: A study from a passive acoustic perspective. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2021**, *31*, 2241–2256. [\[CrossRef\]](#)
12. Schakner, Z.A.; Blumstein, D.T. Behavioral biology of marine mammal deterrents: A review and prospectus. *Biol. Conserv.* **2013**, *167*, 380–389. [\[CrossRef\]](#)
13. Lavery, T.J.; Roudnew, B.; Gill, P.; Seymour, J.; Seuront, L.; Johnson, G.; Mitchell, J.G.; Smetacek, V. Iron defecation by sperm whales stimulates carbon export in the Southern Ocean. *Proc. R. Soc. B Biol. Sci.* **2010**, *277*, 3527–3531. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Roman, J.; McCarthy, J.J. The whale pump: Marine mammals enhance primary productivity in a coastal basin. *PLoS ONE* **2010**, *5*, e13255. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Smith, L.V.; McMinn, A.; Martin, A.; Nicol, S.; Bowie, A.R.; Lannuzel, D.; van der Merwe, P. Preliminary investigation into the stimulation of phytoplankton photophysiology and growth by whale faeces. *J. Exp. Mar. Biol. Ecol.* **2013**, *446*, 1–9. [\[CrossRef\]](#)
16. Lyle, J.M.; Willcox, S.T. *Dolphin and Seal Interactions with Mid-Water Trawling in the Small Pelagic Fishery, Including an Assessment of Bycatch Mitigation Strategies*; Final Report Project R05/0996; Tasmanian Aquaculture and Fisheries Institute: Hobart, Australia; Australian Fisheries Management Authority: Canberra, Australia, 2008.

17. Baker, B.; Hamilton, S.; McIntosh, R.; Finley, L. *Technical Review: Development and Application of Bycatch Mitigation Devices for Marine Mammals in Mid-Water Trawl Gear*; Report Prepared for the Department of the Environment (on behalf of the Expert Panel); Department of the Environment: Canberra, Australia, 2014; Volume 12.
18. Lee, G.H.; Song, D.H.; Kim, H.Y. Characteristics of catch losses in stow nets with finless porpoise excluder devices and a strategy to reduce them. *Reg. Stud. Mar. Sci.* **2022**, *50*, 102147. [\[CrossRef\]](#)
19. Lee, G.H.; Kim, H.Y.; Song, D.H. The opening efficiency difference of guide net in finless porpoise escape device by the type of extension net in stow net. *J. Korean Soc. Fish. Ocean Technol.* **2021**, *59*, 271–282. [\[CrossRef\]](#)
20. Lee, J.H.; Kim, E.H.; Lee, K.; Park, K.J.; An, Y.R.; Kim, H.W.; Sohn, H.; Choi, S.G. Occurrence and spatial distribution of marine mammals by sighting surveys in Korean waters during 2011–2020. *Korean J. Fish. Aquat. Sci.* **2022**, *55*, 938–945. [\[CrossRef\]](#)
21. Park, K.J.; An, Y.R.; Kim, Z.G.; Choi, S.G.; Moon, D.Y.; Park, J.E. Abundance estimates of the Minke whale *Balaenoptera acutorostrata*, in the East Sea, Korea. *Korean J. Fish. Aquat. Sci.* **2009**, *42*, 642–649. [\[CrossRef\]](#)
22. Lee, D.; An, Y.R.; Park, K.J.; Kim, H.W.; Lee, D.; Joo, H.T.; Oh, Y.G.; Kim, S.M.; Kang, C.K.; Lee, S.H. Spartial distribution of common Minke whale (*Balaenoptera acutorostrata*) as an indication of a biological hotspot in the East Sea. *Deep Sea Res. Part II Top. Stud. Oceanogr.* **2017**, *143*, 91–99. [\[CrossRef\]](#)
23. Fryer, R.J. A model of between-haul variation in selectivity. *ICES J. Mar. Sci.* **1991**, *48*, 281–290. [\[CrossRef\]](#)
24. Kinacigil, H.T.; İlkyaz, A.T.; Akyol, O.; Metin, G.; Çira, E.; Ayaz, A. Growth parameters of red mullet (*Mullus barbatus* L., 1758) and seasonal cod-end selectivity of traditional bottom trawl nets in Izmir Bay (Aegean Sea). *Acta Adriat.* **2001**, *42*, 113–123.
25. Özbilgin, H.; Tosunoglu, Z.; Tokac, A.; Metin, G. Seasonal variation in the trawl coded selectivity of red mullet (*Mullus barbatus*). *Turk. J. Fish. Aquat. Sci.* **2011**, *11*, 191–198. [\[CrossRef\]](#)
26. Bahamon, N.; Sardà, F.; Suuronen, P. Improvement of trawl selectivity in the NW Mediterranean demersal fishery by using a 40 mm square mesh codend. *Fish. Res.* **2006**, *81*, 15–25. [\[CrossRef\]](#)
27. Jørgensen, T.; Ingólfsson, Ó.A.; Graham, N.; Isaksen, B. Size selection of cod by rigid grids—Is anything gained compared to diamond mesh codends only? *Fish. Res.* **2006**, *79*, 337–348. [\[CrossRef\]](#)
28. Bak-Jensen, Z.; Herrmann, B.; Santos, J.; Jacques, N.; Melli, V.; Feekings, J.P. Fixed mesh shape reduces variability in codend size selection. *Can. J. Fish. Aquat. Sci.* **2022**, *79*, 1820–1829. [\[CrossRef\]](#)
29. Millar, R.B.; Walsh, S.J. Analysis of trawl selectivity studies with an application to trouser trawls. *Fish. Res.* **1992**, *13*, 205–220. [\[CrossRef\]](#)
30. Wileman, D.A.; Ferro, R.S.T.; Fonteyne, R.; Millar, R.B. *Manual of Methods of Measuring the Selectivity of Towed Fishing Gears*; ICES Cooperative Research Report; ICES: Copenhagen, Denmark, 1996; Volume 215, pp. 1–216.
31. Millar, R.B.; Fryer, R.J. Estimating the size-selection curves of towed gears, traps, nets and hooks. *Rev. Fish Biol. Fish.* **1999**, *9*, 89–116. [\[CrossRef\]](#)
32. Erzini, K.; Gonçalves, J.M.S.; Bentes, L.; Moutopoulos, D.K.; Casal, J.A.H.; Soriguer, M.C.; Puente, E.; Errazkin, L.A.; Stergiou, K.I. Size selectivity of trammel nets in southern European small-scale fisheries. *Fish. Res.* **2006**, *79*, 183–201. [\[CrossRef\]](#)
33. Brooks, M.E.; Melli, V.; Savina, E.; Santos, J.; Millar, R.; O'Neill, F.G.; Veiga-Malta, T.; Krag, L.A.; Feekings, J.P. Introducing selfisher: Open source software for statistical analyses of fishing gear selectivity. *Can. J. Fish. Aquat. Sci.* **2022**, *79*, 1189–1197. [\[CrossRef\]](#)
34. Korean Law Information Center. Enforcement Decree of the Fisheries Act. 2026. Available online: <https://www.law.go.kr/LSW/eng/engLsSc.do?menuId=2§ion=lawNm&query=fisheries&x=20&y=19#liBgcolor18> (accessed on 15 June 2026).
35. Lee, J.H.; Lee, G.H.; Choi, K.S.; Kim, H.Y. Performance estimation of bycatch reduction devices for coastal shrimp beam trawl using dynamic modeling. *J. Korean Soc. Fish. Mar. Sci. Educ.* **2024**, *36*, 1167–1179. [\[CrossRef\]](#)
36. Kim, B.T. A study on the consumption characteristics of mackerel by origin. *Ocean Policy Res.* **2017**, *32*, 185–207. [\[CrossRef\]](#)
37. Moon, S.Y.; Choi, J.H.; Lee, H.W.; Kim, J.N.; Heo, J.S.; Gwak, W.S.; Lee, Y.D. Distribution and characteristics of Pacific herring *Clupea pallasii* spawning beds in Jinhae bay, Korea. *Korean J. Fish. Aquat. Sci.* **2019**, *52*, 534–538. [\[CrossRef\]](#)
38. Sim, S.; Lee, J.; Oh, S. An analysis of the effects in the TAC system by analyzing catch of TAC target species. *Ocean Polar Res.* **2020**, *42*, 157–169. [\[CrossRef\]](#)
39. Lee, Y.M.; Kim, J.K. Review of the scientific name for two species of Genus Pampus (Stromateldae) in Korea. *Korean J. Ichthyol.* **2023**, *35*, 244–252. [\[CrossRef\]](#)
40. Kang, H.W.; Han, J.C.; Jin, Y.G.; Lee, K.M.; Jeong, Y.M. Morphometric characteristics between silver pomfret, *Pampus punctatissimus* and Korean pomfret, *Pampus argenteus*. *J. Fish. Mar. Sci. Educ.* **2021**, *33*, 994–1002. [\[CrossRef\]](#)
41. Matsushita, Y.; Inoue, Y. Variation of square mesh coded selectivity for walleye pollock *Theragra chalcogramma* with respect to difference in body shape. *Nippon Suisan Gakkaishi* **1997**, *63*, 23–29. [\[CrossRef\]](#)
42. Liang, Z.; Horikawa, H.; Tokimura, M.; Tokai, T. Effect of cross-sectional shape of fish body on mesh selectivity of trawl coded. *Nippon Suisan Gakkaishi* **1999**, *65*, 441–447. [\[CrossRef\]](#)
43. Petrakis, G.; Stergiou, K.I. Size selectivity of diamond and square mesh codends for four commercial Mediterranean fish species. *ICES J. Mar. Sci.* **1997**, *54*, 13–23. [\[CrossRef\]](#)

44. Lee, D.J.; Kang, S.; Choi, K.H.; Jung, K.M. Species composition and seasonal variations of fishes collected by set net in coastal waters of Gijang, Korea. *Korean J. Fish. Aquat. Sci.* **2014**, *47*, 983–996. [\[CrossRef\]](#)
45. Huh, S.H. Studies on the fishery biology of pomfrets, *Pampus* spp. in the Korean waters 4. Food of pampus echino gaster. *Korean J. Fish. Aquat. Sci.* **1989**, *22*, 291–293.
46. Kang, Y.J.; Lee, D.W.; Hong, B.Q.; Kim, Y.S. Studies on the fishery biology of pomfrets, *Pampus* spp. In the Korean waters 3. Age and growth of Korean pomfret, pampus echino gaster, from the East China Sea. *Korean J. Fish. Aquat. Sci.* **1989**, *22*, 281–290.
47. Mashiro, M. *Fishery Biology of Ribbon Fish, Trichiurus lepturus in Western Wakasa Bay*; Kyoto Institute of Oceanic and Fishery Science Special Report; Kyoto Institute of Oceanic and Fishery Science: Miyazu, Japan, 1991; Volume 3, pp. 1–74.
48. Kenji, K. Study on the improvement of the productivity of trawl fishery. *J. Tokyo Univ. Fish.* **1960**, *4*, 1–158.
49. Park, J.S.; Kim, S.J.; Kim, S.G. A study on the behaviour of fish schools in the process of catch of the purse seine fishing method. *J. Korean Soc. Fish. Ocean Technol.* **1997**, *33*, 173–182.
50. Koo, M.S.; Kim, S.J. Studies on the development of the fishing system of set net in the coast of Jeju Island 3. The model experiment of fyke net for construction improvement. *J. Korean Soc. Fish. Ocean Technol.* **2004**, *40*, 37–46. (In Korean with English abstract) [\[CrossRef\]](#)
51. Madsen, N.; Hansen, K.E.; Moth-Poulsen, T. The kite cover: A new concept for covered codend selectivity studies. *Fish. Res.* **2001**, *49*, 219–226. [\[CrossRef\]](#)
52. Jung, J.M.; Matsushita, Y.; Hirose, M.; Sakai, T.; Kawauchi, Y.; Yoda, M. Catch difference of groundfishes between two survey trawl nets having differing headrope and groundrope configurations in the East China Sea. *Fish. Sci.* **2021**, *87*, 263–270. [\[CrossRef\]](#)
53. Sabu, S.; Boopendranath, M.R. Studies on Soft Bycatch Reduction Devices for Selective Trawling. Ph.D. Thesis, Cochin University of Science and Technology, Kochi, India, 2008.
54. Kim, H.; Park, G.; Lee, S.; Kim, J.; Oh, W.; Park, M.; Lee, K.H. A studies of the passive acoustic monitoring of finless porpoise *Neophocaena asiaeorientalis* around Hadong. *Korean J. Fish. Aquat. Sci.* **2025**, *58*, 60–70. [\[CrossRef\]](#)
55. National Oceanic and Atmospheric Administration. Marine Mammal Protection Act Comparability Finding Determinations for Harvesting Nations. 2025. Available online: <https://www.fisheries.noaa.gov/international-affairs/marine-mammal-protection-act-comparability-finding-determinations-harvesting> (accessed on 15 June 2026).
56. Fish, F.E.; Hui, C.A. Dolphin swimming—A review. *Mammal Rev.* **1991**, *21*, 181–195. [\[CrossRef\]](#)
57. Fertl, D.; Leatherwood, S. Cetacean interactions with trawls: A preliminary review. *J. Northwest Atl. Fish. Sci.* **1997**, *22*, 219–248. [\[CrossRef\]](#)

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