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EDITED BY
Valentina Melli,
Technical University of Denmark,
Denmark

REVIEWED BY
Lotte Kindt-Larsen,
Technical University of Denmark,
Denmark
Jesse F. Senko,
Arizona State University, United States

*CORRESPONDENCE
John H. Wang
john.wang@noaa.gov

†These authors have contributed equally to this work and share senior authorship

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Reducing sea turtle bycatch with net illumination in an Indonesian small-scale coastal gillnet fishery

Dwi Ariyoga Gautama[1†], Hendro Susanto[2], Mochammad Riyanto[3], Ronny I. Wahju[3], Michael Osmond[4] and John H. Wang[5*†]

[1]United Nations Development Program - Indonesia, Jakarta, Indonesia, [2]World Wildlife Fund (WWF) – Indonesia, Jakarta, Indonesia, [3]Department Fisheries Resources Utilization, IPB University, Bogor, Indonesia, [4]World Wildlife Fund (WWF)-USA, Washington, DC, United States, [5]Pacific Islands Fisheries Science Center, NOAA Fisheries, Honolulu, HI, United States

Small-scale fisheries are economically and culturally important throughout the world's coastal waters. These fisheries, however, often have high bycatch rates of protected marine species. Bycatch in small scale gillnet fisheries is thought to be a major driver behind the declines of several sea turtle populations. Recent studies addressing this issue have identified net illumination as a potentially effective bycatch reduction technology (BRT) to reduce sea turtle interactions with gillnet fisheries. In Southeast Asia, small-scale gillnet fisheries make up a large components of fishing effort often in areas that overlap with important sea turtle habitat. We conducted controlled experiments of net illumination as a potential BRT to reduce sea turtle bycatch in a coastal gillnet fishery based in Paloh, West Kalimantan, Indonesia. Results indicated that net illumination significantly reduced multi-species sea turtle bycatch by 61.4% and specifically green sea turtles (*Chelonia mydas*) by 59.5%, while the CPUE of total catch and target species remained similar. Moreover, this study suggests that Indonesian fishers can increase their overall market value when using net illumination as the market value per unit effort (MVPUE) of both the total catch and target catch showed significant increases. These results suggest that net illumination could be an effective sea turtle conservation tool for small-scale coastal gillnet fisheries in Indonesia and potentially throughout Southeast Asia. In addition, data from the control treatments of this study also provided the first observer based sea turtle bycatch estimate for a small-scale gillnet fishery in Southeast Asia. Challenges to the broad scale implementation of net illumination to reduce this bycatch of sea turtles include the cost, availability of the technology, socialization of the BRT to fishers, and government interest and support for net illumination as a tool for bycatch reduction.

KEYWORDS

bycatch, gillnet fisheries, Indonesia, LEDs, net illumination, sea turtles, visual cues

Introduction

Small-scale fisheries (SSFs) are found throughout the world's coastal communities and make up the largest segment of the global fishing fleet (Rousseau et al., 2019). These fisheries contribute to a significant portion of the world's catch while providing critical employment, income, and food security to large segments of fishers and their communities (Teh and Sumaila, 2013; Béné et al., 2016; Teh and Pauly, 2018; Watson and Tidd, 2018). SSFs are often diverse, decentralized, and highly dynamic, all of which makes them inherently challenging to manage (Chuenpagdee et al., 2003; Finkbeiner, 2015; Smith and Basuro, 2019). These fisheries are often characterized by vessels lacking in significant mechanization and technology, such as net reels or winches, GPS, depth gauges, or fish finders. They are, however, associated with large numbers of individual vessels that cumulatively contribute to sizeable fishing effort in productive coastal waters (Chuenpagdee et al., 2003; Alfaro-Shigueto et al., 2010; Alfaro-Shigueto et al., 2011; Rahmantya et al., 2015; Halim et al., 2019). As such, SSFs can be a significant source of incidental catch, or bycatch, of many marine taxa which may contribute to the declines of sea turtle, cetacean, elasmobranch, and seabird populations (Soykan et al., 2008; Mangel et al., 2010; Anderson et al., 2011; Žydelis et al., 2013; Lewison et al., 2014). In particular, studies indicate that small-scale coastal gillnet fisheries are a major threat to certain sea turtle populations (Peckham et al., 2007; Wallace et al., 2010; Alfaro-Shigueto et al., 2011; Wallace et al., 2013; Senko et al., 2014b).

In Indonesia, small-scale fisheries are characterized by fishing vessels that operate either without engines, utilize outboard engines, or have less than 10 gross tonnage (GT) in capacity (Rahmantya et al., 2015; CEA, 2018; Halim et al., 2019). This segment of Indonesia's fisheries makes up the largest proportion of the nation's fishing fleet and is estimated at over 550,000 vessels operating in near-shore, coastal waters (Rahmantya et al., 2015; CEA, 2018). While the fishing gear varies and changes throughout the year, gillnets are often a common gear type in these coastal fisheries (Rahmantya et al., 2015).

There are six sea turtle species in Indonesia's coastal waters - green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricate*), olive ridley (*Lepidochelys olivacea*), leatherback (*Dermochelys coriacea*), loggerhead (*Carreta carreta*), and flatback (*Natator depressa*) (Dermawan et al., 2009; Dermawan et al., 2015b). Sea turtles in this region use coastal waters and beaches as important foraging areas, migratory routes, and rookery sites (Dermawan et al., 2015b). Despite being protected by Indonesian Law since 1999, several sea turtle populations show declines due in part to the degradation of nesting beaches, illegal harvesting of eggs and individuals, and bycatch in fisheries (NMFS, 2013; Tapilatu et al., 2013; Casale and Matsuzawa, 2015; Seminoff, 2015; Dermawan et al., 2015a; NMFS, 2016; Senko et al., 2022a). Bycatch poses a serious risk in Indonesian coastal waters because substantial fishing effort from small-scale fisheries overlap with sea turtle habitats (Dermawan et al., 2015a; Gautama et al., 2018). As such, reducing sea turtle bycatch in these fisheries is as a key priority in Indonesia's *National Action Plan for the Conservation of Sea Turtles* (Dermawan et al., 2015b).

Bycatch reduction technologies (BRTs) have been developed and successfully implemented to mitigate sea turtle interactions for several fishing gear types. These include the use of circle hooks in longline fisheries (Watson et al., 2005; Swimmer et al., 2017) and turtle excluder devices (TEDs) in shrimp trawl fisheries (Jenkins, 2012). Potential gear-based solutions for reducing bycatch in gillnet fisheries include buoyless nets, low profile nets, tie-downs, and the use of mid water nets (Gilman et al., 2010; Peckham et al., 2016).

One strategy for developing BRTs in gillnet fisheries is to utilize the sensory capacities (e.g., auditory, chemosensory, electro-sensory, or visual physiology) of bycatch species as a foundation for solutions (Southwood et al., 2008; Dawson et al., 2013; Jordan et al., 2013; Schakner and Blumstein, 2013; Martin and Crawford, 2015). Recently, studies have used LEDs (light emitting diodes) with wavelengths that are in the sensitivity range of sea turtle vision to illuminate gillnets fished at night to create a visual cue. These illuminated nets have been shown to decrease sea turtle bycatch while maintaining target catch rates (Wang et al., 2010; Wang et al., 2013; Ortiz et al., 2016; Virgili et al., 2018; Kakai, 2019; Bielli et al., 2020; Darquea et al., 2020; Allman et al., 2020). Subsequently, net illumination has also been shown to reduce seabird (Mangel et al., 2018), small cetacean bycatch (Bielli et al., 2020), and total discarded biomass (Senko et al., 2022b). The use of net illumination as a BRT, however, has not been tested in Indonesia nor in any Southeast Asian coastal gillnet fishery.

The goal of this study is to examine the efficacy of net illumination with green LED lights as a potential sea turtle BRT in an Indonesian gillnet fishery off the coast of western Kalimantan. The fishery is a surface driftnet fishery that occurs immediately offshore adjacent to a sea turtle nesting beach and in important foraging grounds for several species of sea turtles (Dermawan et al., 2015a). A secondary objective is to quantify sea turtle bycatch rates, with onboard observers, in a region where there is a lack of sea turtle bycatch data (Wallace et al., 2010; Wallace et al., 2013). Taken together, this study provides a unique opportunity to test an emerging BRT and assess sea turtle bycatch in Southeast Asia, a suspected global bycatch hotspot region where both assessments and bycatch solutions are conspicuously lacking (Wallace et al., 2010; Wallace et al., 2013; Lewison et al., 2014).

Materials and methods

Fishery observations and experimental trials with net illumination were conducted along the Northwest coast of

Paloh, Sambas District, West Kalimantan (Figure 1). Trials utilized standard fishing operations and were part of regular fishing trips from vessels departing the port of Liku, Paloh District, West Kalimantan from April 2014 to June 2017. These fishing boats were wooden vessels of approximately 5 to 7 GT with lengths of 12 - 15 m. The nets used in this fishery were surface drift gillnets made of polyethylene ropes and composed of monofilament net panels that had mesh with a stretched diagonal of 203 mm (8 inches). When deployed, each net panel was 8 m high and 23 m long. Small poly-vinyl chloride (PVC) floats were incorporated in the float line while lead weights were tied into the (bottom) lead line. The number of net panels set each night varied slightly for each gillnet with the total net length ranging from 1.17 km to 1.38 km. Following the standard practice of this fishery, nets were deployed during late afternoon, soaked overnight, and retrieved by hand during early morning (Damora et al., 2018).

Onboard observers were trained to identify, handle, and collect data on target species, commercially valuable non-target species retained for sale, and bycatch species. Observers collected operational fishing data, gear characteristics, information on each net set (*e.g.* vessel size, location, time of setting and hauling, net length), and catch information). The primary target species in this fishery included the pomfret species *Pampus chinensis,*

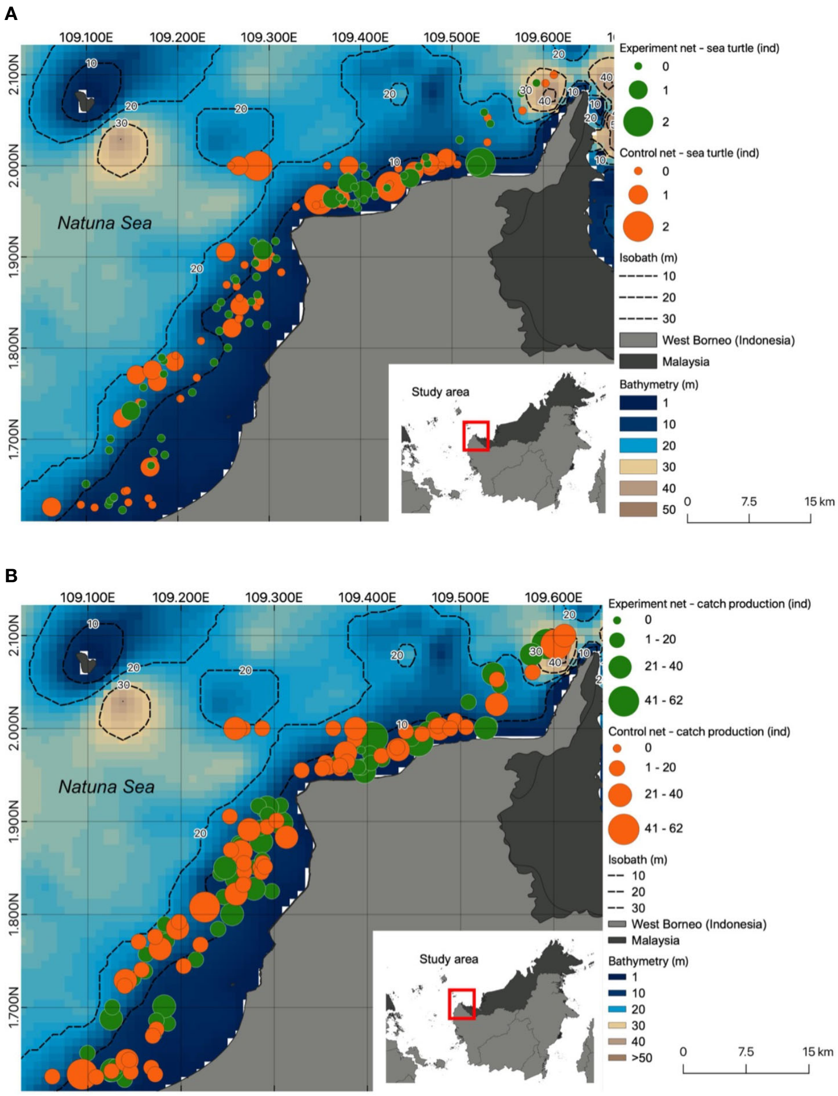

FIGURE 1
Location of gillnet sets in Paloh waters, West Kalimantan, Indonesia. Control nets are shaded in orange and experimental, illuminated nets are shaded green. The level of catch is shown by the size of the circles. **(A)** Location and quantity of sea turtle bycatch for each net set. **(B)** Location and quantity of marketable catch for each set.

Pampus argenteus, and *Parastromateus niger* (Damora et al., 2018). The fishery also captured several commercially valuable non-target species, which included *Lutjanus griseus, Caranx sexfasciatus, Arius thalassinus, Chinocentrus dorab, Myliobatis tobijei, Himantura gerrardi Gymnura poecilura, Eletheronema tetradactylum, Chorinemus tala*, and *Scomberomorus commersonii*, that were retained and sold (Damora et al., 2018). When possible, observers followed the catch to the fish buyers and noted the market value of the total catch, the target catch, and the commercially valuable, non-target catch. For sea turtles, the species was recorded and the curved carapace length (CCL) was measured. Turtles caught alive were released according to technical guidelines issued by Indonesia's Ministry of Marine Affairs and Fisheries (MMAF, 2015) (Dermawan et al., 2009; Dermawan et al., 2015a) and the National Oceanic and Atmospheric Administration (NOAA) (Epperly et al., 2004).

To determine the effects of net illumination on sea turtle bycatch and target catch, we used a paired experimental approach in which control nets were traditional nets using standard fishing practices, while experimental nets were equipped with green spectrum LEDs fishing lights (Centro Power Light, Model CM-1) that produced constant illumination (i.e. these were not the flashing LED lights). The experimental nets were fished identical to control nets (Wang et al., 2010; Wang et al., 2013; Ortiz et al., 2016; Mangel et al., 2018; Bielli et al., 2020; Senko et al., 2022b). Lights had a peak wavelength of 500 nm and were placed every 10-m on the floatline of the experimental net. During paired experimental trials, both a control and an experimental net were deployed on the same night and in the same area (*i.e.* within 1 km to 2 km of each other) as in other comparable study designs (Wang et al., 2010; Wang et al., 2013; Ortiz et al., 2016; Mangel et al., 2018; Bielli et al., 2020; Senko et al., 2020).

For each net, the catch-per-unit-effort (CPUE) for all the target fish species, all the commercially valuable, retained non-targeted species, and all sea turtles were calculated as the number of individuals captured/([net length/1 km] X [net soak time/ 12 h]) (Wang et al., 2013). In addition, when market data was available, we calculated the market value-per-unit-effort (MVPUE) in Indonesian rupiah (IDR) for each net as the market value of the catch/([net length/1 km] X [net soak time/ 12 h]). We used the Wilcoxon matched-pairs signed-rank test paired by net to determine the p-value for the difference in CPUE for each catch type between control and experimental nets (Wang et al., 2010; Mangel et al., 2018; Senko et al., 2022a). All analyses were performed with GraphPad Prism (ver 8.3.0).

Results

Fishing effort

A total of 70 pairs of control and illuminated nets were deployed during the trials (Figure 1). The overall fishing effort for the control treatment was 86.8 (km X 12 h) while the total illuminated net treatment effort was 84.5 (km X 12 h) (Table 1). Control nets averaged (mean ± SE) 12.4 ± 0.5 h of soak time and illuminated nets averaged 12.1 ± 0.4 h, while net length for both control and illuminated nets was a mean of 1.20 ± 0.01 km (Table 1). The mean fishing effort for control nets was 1.24 ± 0.05 (km X 12 h) and 1.21 ± 0.04 (km X 12h) for illuminated nets (Table 1).

Effects of net illumination on fish catch and value

Control nets captured a total of 2,176 individual finfish and elasmobranchs, of which 1,124 (51.6% of the total catch) were bycatch that were either discarded at sea, consumed by the crew, or utilized as bait for other fisheries. The total marketable catch consisted of 1,052 fish (48.3% of the total catch) with 507 individuals as the primary target species and 545 as commercially valuable retained non-targeted catch (Table 2). Experimental nets had a catch of 2,368 of which 1,286 (53% of the total catch) was bycatch (Table 2). The marketable catch was 1,100 (46.5% of the total individual pieces) of which 611 were primary target species and 489 were commercially valuable non-targeted species (Table 2).

Comparisons between the CPUE in control nets and illuminated net for total marketable catch, target catch, and non-target catch with the Wilcoxon matched-pairs signed-rank test detected no significant differences (Table 3; Figure 2). While not statistically significant, illuminated nets had increases in total catch by 9.3% and target CPUE by 17.1% (Table 3). When possible, observers followed the catch to the fish buyers. Market data for the target catch was collected for 67 paired sets, while market data of the non-target catch was recorded for 48 paired

TABLE 1 Summary of fishing effort by net type (control = nets without LED illumination, Illuminated = nets with LED illumination) for paired gillnets.

Net type	Sets	Total effort (km X 12 h)	Mean soak time ± SE (h)	Mean net length ± SE (m)	Mean fishing effort ± SE (km X 12 h)
Control	70	86.8	12.4 ± 0.5	1.20 ± 0.01	1.24 ± 0.05
Illuminated	70	84.5	12.1 ± 0.4	1.20 ± 0.01	1.21 ± 0.04

SE, standard error.

TABLE 2 The amount of total catch, bycatch, total marketable catch, target catch (*Parastromateus niger, Pampus argenteus, and Pampus chinensis*), marketable non-target catch, and sea turtle bycatch for the paired control and illuminated net treatments.

Catch	Paired trials	Control nets	Illuminated nets
Total catch	**70**	**2,176**	**2,368**
Bycatch	70	1,124 (51.6%)	1,268 (53.5%)
Total marketable catch	70	1,052 (48.3%)	1,100 (46.5%)
Target catch	70	507 (23.3%)	611 (25.8%)
Non-target catch	70	545 (25.0%)	489 (20.7%)
Total sea turtle bycatch	**70**	**24**	**9**
Green sea turtles	70	14	6
Olive ridley sea turtles	70	7	1
Hawksbill sea turtles	70	3	2

Percentages for the total catch are for the percent amount of total catch within either control nets or illuminated nets.

TABLE 3 Comparisons between the mean CPUE for control and illuminated nets for the total marketable catch, the target catch (*Parastromateus niger, Pampus argenteus, and Pampus chinensis*), the marketable non-target catch, and the total sea turtle bycatch.

		Net treatment (mean CPUE ± SE)			
	Sets	Control	Illuminated	% change	p-value
Total marketable catch	**70**	**12.43 ± 1.14**	**13.59 ± 1.29**	**+9.3%**	**0.370**
Target catch	70	6.21 ± 0.73	7.27 ± 0.69	+17.1%	0.096
Non-target catch	70	6.22 ± 0.76	6.32 ± 1.09	+1.5%	0.655
Total sea turtle bycatch	**70**	**0.28 ± 0.06**	**0.11 ± 0.04**	**-61.4%**	**0.006***
Green sea turtles	70	0.18 ± 0.05	0.7 ± 0.03	-59.5%	0.039*

Percent change represents the difference in mean CPUE between control and illuminated nets. P-values represent the differences between control and illuminated nets analyzed using a Wilcoxon signed-rank test paired by net, with significant differences indicated with an asterisk.
CPUE = number of catch per (1 km of net X 12 h), SE, standard error.

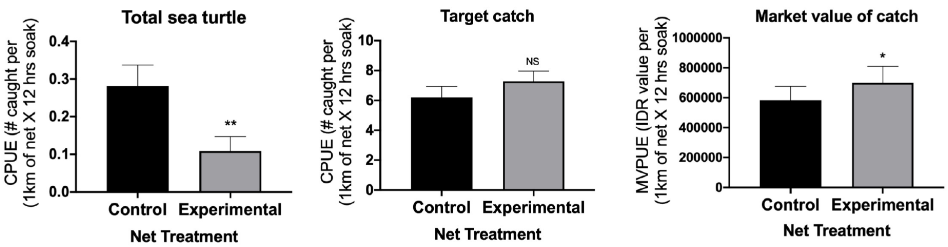

FIGURE 2
Comparison of total sea turtle mean CPUE [catch per unit effort = number caught/(1km of net X 12 hrs soak time)], mean target catch (*Parastromateus niger, Pampus argenteus, and Pampus chinensis*), and mean MVPUE (market value per unit effort) of the total catch between control nets and illuminated nets. Error bars are standard error (SE), NS, not significant, ** indicates p < 0.01, * indicates p < 0.05).

sets. For only 45 net pairs, the market data for both target and non-target catch was obtained. Analysis with the Wilcoxon matched-pairs signed-rank test showed that there was a significant (p-value = 0.023, Table 4) increase of 20.2% in the MVPUE of the total catch and a significant (p-value = 0.013, Table 4) increase of 15.0% in the target catch MVPUE when illuminated nets were used (Figure 2).

Effects of net illumination on sea turtle bycatch

A total of 33 sea turtles were caught in the 70 paired net trials, with 24 turtles caught in the control nets and 9 in the experimental nets (Figure 1B, Table 2). Most sea turtles caught were green turtles, with 14 in control nets and 6 in illuminated

TABLE 4 Comparison of the mean market value per unit effort (MVPUE, value in thousands (K) of Indonesian rupiah, SE=standard error) between control and illuminated net treatment for the total market value of the catch, the target catch (*Parastromateus niger, Pampus argenteus, and Pampus chinensis*), and commercially valuable retained non-target catch.

		Net treatment (mean MVPUE ± SE)			
	Sets	Control	Illuminated	% change	p-value
Total catch value	45	582.5K ± 93.5K	699.0K ± 111.1K	+20.2%	0.023*
Target catch value	67	459.9K ± 74.2K	529.0K ± 75.2K	+15.0%	0.013*
Non-target catch	48	91.5K ± 13.6K	108.9K ± 17.0K	+19.0%	0.461

As catch was followed to the market, market values were not available for all 70 paired sets. Percent change represents the difference in mean CPUE between control and illuminated nets. P-values represent the differences between control and illuminated nets analyzed using a Wilcoxon signed-rank test paired by net, with significant differences indicated with an asterisk.

nets. Eight olive ridley turtles were caught, with 7 in control nets and one in an illuminated net. Five hawksbill turtles were also caught, with 3 in control nets and 2 in illuminated nets. Sea turtles caught in these trials were all released alive. Of the 33 sea turtles captured, only 13 had CCL measurements (9 green, 1 hawksbill, 3 olive ridley sea turtles). For the CCL measurements taken from green turtles, 8 were from control nets and one was from illuminated nets. The mean CCL for the 9 green turtles caught from both net treatments was 47.1 cm ± 1.9 SE. For hawksbill turtles, the CCL measurement from the one turtle from the control net was 42.0 cm. For olive ridley turtles, all 3 CCL measurements were made on turtles caught in the control net and the mean CCL was 51.3 cm ± 5.0 SE.

All species of turtles were pooled together to compare the total sea turtle CPUE between control and illuminated nets. For the 70 pairs of nets, the mean total sea turtle CPUE in the control nets was 0.28 ± 0.06 SE and a mean total sea turtle CPUE in the illuminated net treatment was 0.11 ± 0.04 SE for the illuminated net treatment (Figure 2; Table 3). Analysis with the Wilcoxon matched-pairs signed-rank test showed that the sea turtle CPUE was significantly ($p = 0.006$; Table 3) lower in illuminated nets by 61.4%. The mean green sea turtle CPUE in the control nets was 0.18 ± 0.05 SE and a mean green sea turtle CPUE in the illuminated net treatment was 0.07 ± 0.03 SE for the illuminated net treatment (Figure 2; Table 3). Analysis with the Wilcoxon matched-pairs signed-rank test showed that the green sea turtle CPUE was significantly decreased ($p = 0.039$; Table 3) in illuminated nets by 59.5%. As the catch of olive ridley and hawksbill sea turtles were much fewer, comparisons between nets were not conducted.

Discussion

This study examines the efficacy of net illumination to reduce sea turtle bycatch in coastal small-scale gillnet fisheries in Southeast Asia, a suspected sea turtle global bycatch hotspot (Wallace et al., 2010; Wallace et al., 2013). Results revealed that net illumination significantly reduced total sea turtle bycatch by 60.7% and specifically, green sea turtle bycatch, by 59.5% in the coastal drift gillnet fishery off the coast of Paloh in West Kalimantan, Indonesia. Moreover, this study suggests that Indonesian fishers can increase their overall market value when using net illumination. Being able to maintain or even increase the overall market value is an important aspect for the adoption of this bycatch reduction gear (Jenkins, 2012; Senko et al., 2014a; Ortiz et al., 2016; Bielli et al., 2020) as it reduces the burden placed on fisheries. In addition, by reducing sea turtle interactions (Figure 3), fishers can avoid the time-consuming and potentially hazardous process of dis-entangling large sea turtles, reduce damage to their gear caused when cutting out turtles from the fishing nets, and limit the subsequent time and expense needed to repair that damage (Panagopoulou et al., 2017). Senko et al. (2022a) also found that the use of net illumination helped significantly increase the efficiency of fishing operations through reducing net retrieval times. These benefits of net illumination, coupled with a cultural taboo in the region for catching and harming sea turtles, are especially important to Indonesian fishers in the Kalimantan region and are further incentives for the adoption of this BRT.

The coastal waters of Indonesia support a sizeable small-scale fishing fleet estimated to be over 550,000 vessels which constitutes a majority of Indonesia's national fishing vessels (Rahmantya et al., 2015; CEA, 2018). As these small-scale fisheries play important socioeconomic and cultural roles in Indonesia's coastal communities, their long-term stability and sustainability requires taking into consideration the needs of protecting endangered, threatened, and protected resources such as sea turtles (Dermawan et al., 2015a; Dermawan et al., 2015b). With gillnets as one of the more common gear types in coastal fisheries (Rahmantya et al., 2015), net illumination is a potentially useful tool to help balance the economic livelihood of Indonesian fishers with a sea turtle bycatch mitigation measure that helps the nation safeguard its protected resources. Similarly, thousands of small-scale coastal gillnet fisheries operating throughout Southeast Asian waters (Pomeroy, 2011; Teh and Sumaila, 2013; Teh and Pauly, 2018) may find this BRT applicable to their fisheries and it could be a much-needed sea turtle conservation tool for the broader region (Wallace et al., 2010; Wallace et al., 2013). Consequently, further

FIGURE 3
Sea turtle bycatch often results in extensive tangling of the nets which reduces the fishing efficacy of large portions of the net. Removing sea turtles from these tangles require substantial effort and time from fishers and can result in significant damage to the fishing gear.

studies will be needed to understand the effectiveness of net illumination as a conservation tool throughout Southeast Asian gillnet fisheries.

The 61.4% reduction in total sea turtle bycatch and 59.5% reduction in green sea turtle bycatch rate found in this study corroborates reductions from Bielli et al. (2020), which reported a 74.4% decrease in green sea turtle bycatch probability in a Peruvian surface drift gillnet fishery. Our results are also in line with sea turtle bycatch reductions found in previous studies that tested illuminated bottom-set gillnets (Table 5). Despite being conducted in disparate fisheries with different target catch species, all these studies showed no change in target catch (Table 5). In our study, we found no change in both total and target catch CPUE, but significant increases in total catch value and target catch MVPUE in illuminated nets. Illuminated nets did have non-significant increases in both total catch and target catch. It is not known whether this was due to increased attraction of target species to the illuminated nets or whether less entangled turtles resulted in less damage to nets leading to better fishing efficiencies of untangled nets. In addition, it is not known whether net illumination had a greater effect on larger, more valuable size classes of target fish species. Regardless, as net illumination reduces sea turtle bycatch in both drift and bottom-set gillnet fisheries while also maintaining target catch across a spectrum of target species from different regions (Table 5; Wang et al., 2010; Wang et al., 2013; Ortiz et al., 2016; Virgili et al., 2018; Allman et al., 2020; Bielli et al., 2020; Darquea et al., 2020; Senko et al., 2022a), there is the potential for broad applicability of net illumination as a sea turtle BRT. It will, however, be important to test this BRT in other gillnet fisheries to understand the effects of net illumination to a specific fishery and discern the nuances necessary to adopt this BRT in that fishery's particular management scheme.

Global assessments of marine megafauna bycatch indicate that gillnet fisheries are often associated with comparatively high rates of sea turtle bycatch (Wallace et al., 2010; Wallace et al., 2013; Lewison et al., 2014). Such assessments, however, draw attention to Southeast Asian small-scale fisheries and gaps in their data on bycatch (Wallace et al., 2010; Wallace et al., 2013; Lewison et al., 2014). This study is the first to report sea turtle

TABLE 5 Published studies testing net illumination as a bycatch reduction technology.

Fishery and testing location	Light source	Effects on bycatch	Effects on target catch	Reported total bycatch	Reported total fishing effort	Citation
Sea turtle bycatch studies						
Baja, MX experimental gillnet	Green chemi-luminescent lights	60% reduction - green sea turtles	No difference	115 sea turtles	12 net sets	Wang et al., 2010
Baja MX, experimental gillnet	Green LEDs	40% reduction - green sea turtles	No difference	187 sea turtles	30 net sets	Wang et al., 2010
Baja, MX experimental gillnet	UV LEDs	40% reduction - green sea turtles	No difference	332 sea turtles	22 net sets	Wang et al., 2013
Peruvian bottom set gillnet fishery	Green LEDs	64% reduction - green sea turtles	No difference	194 sea turtles	228 net sets	Ortiz et al., 2016
Italian bottom set gillnet fishery	UV LEDs	100% reduction - loggerhead turtles	No difference	16 sea turtles	669 net panels	Virgili et al., 2018
Kenyan bottom set gillnet fishery	Green LEDs	64.3% reduction – mixed species with sea turtles (mainly green turtles)	No difference	86 sea turtles	80 net sets	Kakai, 2019
Peruvian gillnet (drift net and bottom set) fisheries	Green LEDs	70 - 74% reduction - mixed species of sea turtles (green, olive ridley, and loggerhead sea turtles)	No difference	131 sea turtles	864 net sets	Bielli et al., 2020
Ecuadorian drift gillnet fishery	Violet LEDs	93% reduction – mixed species of sea turtles (olive ridley, green, and leatherback sea turtles)	No difference	32 sea turtles	146 net sets	Darquea et al., 2020
Ghanaian gillnet fishery	Green LEDs	81% reduction – mixed species; 88% reduction of leatherbacks, 81% reduction of olive ridleys	No difference	222 sea turtles	9,761 net sets	Allman et al., 2020
Other bycatch taxa studies						
Peruvian bottom set gillnet fishery	Green LEDs	85% reduction – guanay cormorants	No difference	45 cormorants	228 net sets	Mangel et al., 2018
Peruvian gillnet (drift net and bottom set) fisheries	Green LEDs	70% and 66% reduction – mixed species of cetaceans	No difference	53 cetaceans	864 net sets	Bielli et al., 2020
Baja, Mexico bottom set gillnet fishery	Green LEDs	63% reduction – total bycatch biomass; 48% reduction in finfish bycatch; 95% reduction in elasmobranchs bycatch, 81% reduction in Humbolt squid bycatch	No difference	2273 kg of bycatch biomass	56 net sets	Senko et al., 2022a

bycatch rates estimated from onboard observers in a Southeast Asian small-scale fishery, which provides an opportunity to estimate the approximate sea turtle bycatch for this fishery. Surveys of the gillnet fishery in Paloh characterizing this fishery indicate that there are at least 48 active vessels based in the villages of Liku, which operate eight months of the year (March through October) (Ernawati, 2013; Gautama et al., 2018). Vessels typically conduct 3-4 trips per month with nets being deployed between 3-5 nights (Ernawati, 2013; Gautama et al., 2018). Using the minimum number of active vessels (48), the smallest number of operating months (8), the fewest number of trips per month (3), the least number of deployments per trip (3), the minimum fishing effort (1 km X 12h) for a set, and the mean sea turtle CPUE from control nets of 0.28 ± 0.06 (sea turtles captured per (1 km X 12 h)) (Table 3) for a simple extrapolation, we conservatively estimate that the drift gillnet fishery in Paloh interacts with approximately 967 sea turtles each year.

This estimated sea turtle bycatch is comparable with other coastal gillnet fisheries that incur high sea turtle bycatch (Peckham et al., 2007; Alfaro-Shigueto et al., 2011). However, it is unknown how bycatch might be spatially distributed across the Paloh fishing grounds, how bycatch rates might change throughout the fishing season, and how individual fisher's operational behaviors might influence bycatch rates. In addition, it is unknown how representative this interaction rate may be for other Indonesian coastal fisheries, or whether this bycatch rate is considerably higher due to the extensive use of the coastal waters by sea turtles in the region. While all sea turtles captured in this study were released alive, the level of post-interaction mortality (Swimmer et al., 2013; Swimmer et al., 2017; Fahlman et al., 2017) is unknown, whether other gillnet gear types such as bottom set gillnets (*i.e.* nets anchored below the water's surface) have a different bycatch mortality rate, and how such bycatch interactions might disrupt sea turtle behaviors, especially those caught during sea turtle nesting season. These unknowns highlight the need to further characterize sea turtle bycatch and post-interaction mortality rates in coastal gillnet fisheries within Indonesia and throughout the Southeast Asian region.

While net illumination has been tested to determine its efficacy in reducing sea turtle bycatch (Table 5), recent studies are also showing that it represents a potential multi-taxa bycatch solution (Table 5). Mangel et al. (2018) found that net illumination reduced guanay cormorant (*Phalacrocorax bougainvillii*) bycatch by 85% in Peruvian bottomset fisheries, while Bielli et al. (2020) showed that the probability of small cetacean bycatch was reduced by 70.8% in surface drift nets. In addition, recent studies showed that the overall bycatch biomass decreased by 63%, with elasmobranch bycatch being decreased by 95% (Senko et al., 2022a). Having a multi-taxa bycatch solution could help further prompt the broader adoption of this BRT as it might simplify gear recommendations for conservation, streamline management requirements, and potentially increase the cost efficiencies for overall bycatch reductions in a fishery (Mangel et al., 2018; Bielli et al., 2020; Senko et al., 2022a).

For net illumination to be broadly adopted in Indonesia, several key challenges remain. These include ensuring that the cost of net illumination is manageable for fishers, increasing exposure and availability of the technology to managers, fishing communities, and fishers, and engaging government agencies to support this BRT. The costs of LED lights used in this study range from $7 USD to $10 USD per light and required battery changes every 30-45 days. While other LED fishing lights, however, can be purchased at lower costs, Ortiz et al. (2016) indicates that the current cost structure for net illumination will likely require support from national ministries, international non-governmental organizations and the broader fisheries industry. However, Bielli et al. (2020) highlights how the cost for this multi-taxa BRT is relatively low compared to other BRTs aimed at only one bycatch taxa (e.g. acoustics deterrent devices or pingers). Nonetheless, only some Indonesian fishers may be able to adopt net illumination with the current price structures, but the majority will find the expense a barrier for adoption that will likely require government or international NGO support.

Due in part to the continued engagement with Indonesia's Ministry of Marine Affairs and Fisheries (MMAF, 2015) throughout all the stages of net illumination testing, MMAF has been supportive of net illumination as a fisheries bycatch reduction technology that could potentially be included in their management of gillnet fisheries. Collaborations between MMAF have also resulted in outreach activities aimed at socializing net illumination to provincial level fishery managers as well as supporting gear trial programs for fishers. These programs allow fishers to try out lights on their nets, become familiar with the benefits of net illumination (*e.g.* less entanglement with sea turtles, less damage to fishing gear, less net repair time, better fishing efficiencies), and allows fishers the opportunity to adapt net illumination in their individual fishing operations. In addition, outreach to Indonesian manufacturers has indicated interest in domestically manufacturing LED fishing lights. Domestic production of fishing lights has the potential to increase their availability and to hopefully help foster an Indonesian made bycatch reduction technology that does not have the additional burden of import tariffs.

As new net illumination technologies (*e.g.* less expensive lights, lights designed specifically for gillnets, lights that have lower power consumption, solar powered LED lights) become available (Senko et al., 2020), existing collaborations make it easier to continue further outreach and testing. Such testing will likely focus not only on the efficacy of net illumination to reduce bycatch, but also on operational efficiencies (*e.g.* faster haul back times and less net repairs). The combined engagement with MMAF at both the national and provincial level, cooperation with domestic industries to manufacture lights, and continued involvement of fishing communities and individual fishers, can serve as a potential template for other regions in Southeast Asia in order to further expand our understanding of how net illumination could be a useful sea turtle BRT in the region's coastal gillnet fisheries.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Pacific Islands Fisheries Science Center (2022): Indonesia SSF bycatch and bycatch reduction technology testing, https://www.fisheries.noaa.gov/inport/item/47725.

Ethics statement

The animal study was reviewed and approved by NOAA Fisheries. All activities for this research were authorized by WWF Indonesia Foundation and conducted under the Indonesia Ministry of Marine Affairs and Fisheries (KKP) permit numbers 15/SJ-KKP/KB/X/2014 and 200/WWF-ID/LGLMOU/X/2014.

Author contributions

DG, HS, MR, RW, MO, and JW designed, collected, and analyzed the study, and all contributed to the manuscript. DG, JW, and MO acquired project funding. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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