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Association of ocean macroplastic debris with stranded sea turtles in the Central Gulf of Thailand

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ABSTRACT: The impact of macroplastic debris (>5 mm) on marine life is a global concern but has rarely been investigated in Thailand. This study investigated the relationship between stranded sea turtles and macroplastics in the Central Gulf of Thailand. Records of stranded turtles (n = 388) from 2017–2020 were analysed retrospectively to determine their interaction with macroplastics. In addition, macroplastics collected from the gastrointestinal (GI) tracts of 30 dead stranded turtles and 13 beaches (along a 100 m transect mid-way between high and low tide) between 2019 and 2020 were investigated. Types and composition of macroplastics were identified with the use of a stereomicroscope and Fourier-transform infrared spectrometer. Green turtles *Chelonia mydas* comprised the majority of stranded turtles (74%, n = 251), and macroplastics (entanglement or ingestion) were the leading cause of death (n = 152). Most stranded turtles were juveniles (65%), and their stranding was significantly correlated with macroplastics ($p < 0.001$). Juveniles were more prone than adults to become entangled ($p = 0.007$), while adults had a higher ingestion rate than juveniles ($p = 0.009$). Plastic fibres were commonly found in the GI tracts (62%, n = 152 of 244) and beaches (64%, n = 74 of 115). Most fibres from the GI tracts (83%, n = 126 of 152) and beaches (93%, n = 68 of 74) were fishing nets made of polyethylene or polypropylene. We conclude that fishing nets are a significant cause of sea turtle stranding in the Central Gulf of Thailand, and this issue requires immediate resolution.

KEY WORDS: Macroplastics · Stranding · Sea turtles · Thailand

1. INTRODUCTION

Ocean plastic debris is a global issue, impacting over 900 marine species through ingestion and entanglement (Ryan 2016, Reinert et al. 2017, Kühn & van Franeker 2020). Depending on its size, marine plastic debris is classified as macroplastics (>5 mm), microplastics (1 µm–5 mm), or nanoplastics (<1 µm) (Merga et al. 2020). While micro- and nanoplastics can be directly consumed by small organisms and accumulate in the food web (Diepens & Koelmans 2018), macroplastics pose a particular problem for large marine animals such as manatees, whales, and turtles as well as sea birds, who become entangled in

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or ingest large debris like fishing nets, potentially resulting in interruption and obstruction of the gastrointestinal (GI) tract (Jacobsen et al. 2010, Reinert et al. 2017, Duncan et al. 2019, Baak et al. 2020). Not only can macroplastics clog the GI tract, but they can also be harmful to animals that consume them due to the persistence of certain toxic chemicals such as plasticisers (Lithner et al. 2011). Additionally, toxic substances (e.g. heavy metals, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls) can accumulate in ocean plastics (Mato et al. 2001, Nakashima et al. 2012, Bouhroum et al. 2019), and certain pathogenic microbes (e.g. *Vibrio* and *Pseudomonas*) can adhere to the surface layer of marine plastics (Kirstein et al. 2016, Viršek et al. 2017, Wu et al. 2019). These chemicals and pathogens have the potential to cause serious diseases in marine animals and jeopardise food security and food safety for humans (Derraik 2002, Teuten et al. 2007, Brennecke et al. 2016, Barboza et al. 2018).

Thailand is among the world's top 10 producers of marine plastics (Jambeck et al. 2015). Nonetheless, research on plastic debris in the seas around Thailand (the Andaman Sea and the Gulf of Thailand) has been limited to 2 studies that determined the incidence of microplastics in demersal and pelagic fishes (Azad et al. 2018, Klangnurak & Chunniyom 2020). According to local media and government agencies, macroplastics are occasionally discovered in the digestive tracts of stranded sea turtles (www.bangkokpost.com/learning/easy/1482917/trash-filled-turtle-in-chanthaburi-highlights-ocean-crisis). Four species of sea turtles have been recently reported in the Gulf of Thailand and the Andaman Sea by the Department of Marine and Coastal Resource (https://km.dmcr.go.th/c_6/d_973); the majority are green turtles *Chelonia mydas*, followed by hawksbill turtles *Eretmochelys imbricata*, while sightings of olive ridley turtles *Lepidochelys olivacea* and leatherback turtles *Dermochelys coriacea* are rare. According to the IUCN (https://www.iucnredlist.org) green turtles are categorised as Endangered, hawkbill turtles are Critically Endangered, while olive ridley and leatherback turtles are Vulnerable.

The Department of Marine and Coastal Resource in Thailand (https://km.dmcr.go.th/c_6/d_2692) has reported that sea turtle populations and nests are decreasing each year, which may be attributed to tourism, fishing, limited nesting areas, and pollution. However, the causes of the population decline and strandings have not been extensively studied. In the present study, we hypothesised that macroplastics are one of the leading causes of the stranding and death of sea turtles in this region. Therefore, the objective of this study was to investigate the association between macroplastics and the sea turtle strandings in the Central Gulf of Thailand.

2. MATERIALS AND METHODS

2.1. Stranded sea turtle data

To determine the relationship between marine plastics and the stranding of sea turtles, we performed a retrospective analysis of the records of 338 stranded turtles along the shores of the Central Gulf of Thailand in 3 provinces (Chumphon, Surat Thani, and Nakhon Si Thammarat; Fig. 1) between 1 January 2017 and 31 July 2020. The stranded turtles were found and reported by local residents and fishermen. Thereafter, staff from the Marine Animal Research and Rescue Centre of Walailak University or the Marine and Coastal Resources Research

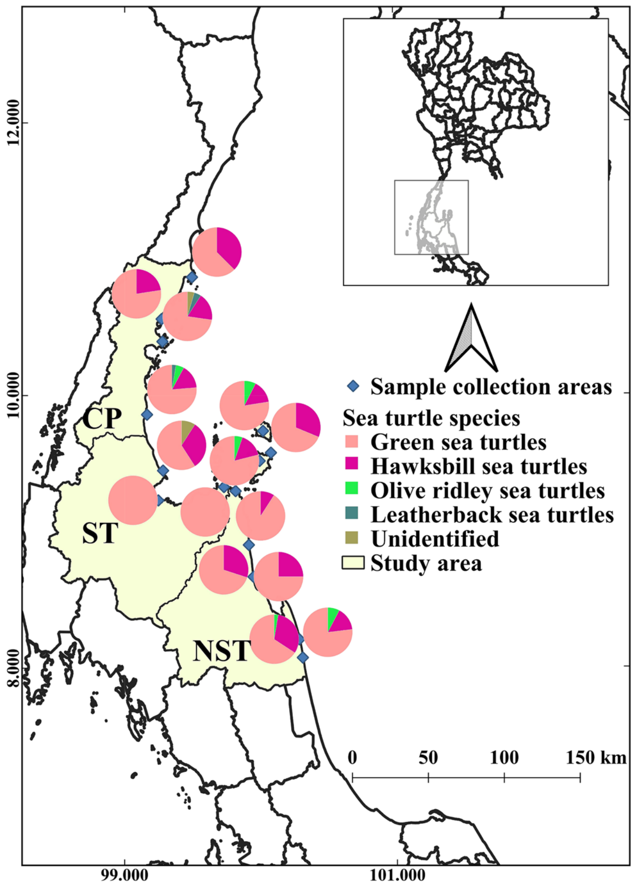


Fig. 1. Study locations in the Central Gulf of Thailand. Samples were collected from Chumphon (CP), Surat Thani (ST), and Nakhon Si Thammarat (NST) provinces. Blue diamonds: sample collection areas. Pie charts illustrate the frequency of each species of stranded sea turtle

Centre (Chumporn province) retrieved the turtles in order to investigate the cause of stranding, health status, or the cause of death, according to standard protocols (Work 2000, Flint et al. 2009, Werneck et al. 2018). For dead turtles, the condition of the carcass was classified as fresh, evident decomposition, advanced decomposition, or mummified (Werneck et al. 2018).

The sex of deceased turtles was determined during necropsy or by examining the tail morphology of live adult turtles (adult males have a significantly longer tail than females); live juveniles and sub-adults could not be sexed (Schofield et al. 2017). Based on previous studies (Bresette et al. 2010, Jensen et al. 2018, Robinson et al. 2021), each stranded turtle was grouped according to its size (curved carapace length, CCL) into the following categories: green turtles: juvenile (<65 cm CCL), sub-adult (65–86 cm CCL), and adult (>86 cm CCL); hawksbill turtles: juvenile (<55 cm CCL), sub-adult (>55–70 cm CCL), and adult (>70 cm CCL); olive ridley turtles: juvenile (<62 cm CCL), sub-adult (62–70 cm CCL), and adult (>71 cm CCL); leatherback turtle: juvenile (<50 cm CCL), sub-adult (50–70 cm CCL), and adult (>70 cm CCL).

2.2. Plastic analysis

After performing a preliminary retrospective analysis, we discovered evidence that macroplastics might be related to sea turtle stranding. Additionally, data collected by the Marine and Coastal Resources Research Centre (https://km.dmcr.go.th/en/c_6/d_982) revealed that green turtles in the Gulf of Thailand usually do not move far from the shore. Therefore, we investigated the types of plastic found in the GI tract of the turtles as well as those found on the beaches.

We hypothesised that the plastic types found on the beaches and in the GI tracts of the turtles might be similar to those in the turtles' feeding areas in the ocean. Therefore, macroplastics obtained from the turtles and the beaches between 2019 and 2020 were analysed. In total, 244 macroplastic items were recovered from the stomach and small intestines of 30 dead stranded turtles (only fresh and evident decom items the beaches).

Ocean macroplastics (>5 mm) were collected from 13 beaches where stranded sea turtles were observed (Fig. 1). These included 5 beaches of Chumphon province (Sairee beach of Muang district, Hat Kho Khao of Lang Suan district, the Fishing village of Thung Tako district, Thung Wua Laen Beach of Pathio district, and Tongsai of Sawi district), 3 beaches of Surat Thani province (Ferry Terminal of Donsak district, Laem Sai Beach of Chaiya district, and Leeled Beach of Punpin District), and 5 beaches of Nakhon Si Thammarat province (Khwaeng Phao Beach of Khanom District, Bang Dee Beach of Sichon District, Ban Tha Sung Bon Beach of Thasala District, Koh Fai Beach of Pak Phanang District, and Chan Chaeng Beach of Hausai). Samples were collected along a 100 m transect mid-way between high and low tide (shoreline width: <6 m) following the sampling procedure of Besley et al. (2017). In total, 115 macroplastic items were collected from the beaches.

Macroplastics (n = 244) were visually categorised as fibre (net or line), bag, foam, straw (for drinking), or hard plastic, followed by confirmation under a stereomicroscope (SMZ460 Zoom, Nikon Instruments) and a Fourier-transform infrared (FTIR) spectrometer using a reference database and plastic materials obtained from local fishermen and stores. FTIR model Tensor 27 equipped with a Platinum-ATR-unit (Bruker Optic) was used to determine the chemical composition of the macroplastics. We co-added 32 scans to achieve an appropriate signal-to-noise ratio, with a spectral resolution of $8\,cm^{-1}$ in a wavenumber range from $4000–400\,cm^{-1}$ (Primpke et al. 2018). The obtained spectra were analysed with the software OPUS 7.5 (Bruker Optik) through comparison with polymer reference spectra from our in-house plastic database and a previous study (Jung et al. 2018a).

2.4. Statistical analysis

Binomial regression was used to predict the probability of the causes of stranding and macroplastics problems (entanglement in fishing nets or ingestion leading to GI obstruction) based on the descriptive variable species (green, hawksbill, or olive ridley turtles) and life history stages (juvenile, sub-adult, or adult). A chi-squared analysis was conducted to determine statistical differences among the groups of sea turtles and between entanglement and ingestion probabilities for the death of sea turtles. All analyses were performed using R statistical software version 4.0.4.

2.5. Animal ethics

This study was approved by the Institutional Animal Care and Use Committee (IACUC) of Walailak University (project number 63-009).

Table 1. Stranding information for different turtle species in the Central Gulf of Thailand from 2017–2020. Badly damaged cadavers or mummified individuals were classified as 'unidentified species'. Macroplastics included entanglement and/or ingestion; health problems included infection or disease; injury was caused by boats. n: number of turtles

Species	% of stranded turtles (n)					% Causes of stranding (n)			
	Viability		Stage of life			Macro-plastics	Health problems	Injury	Unknown
	Live	Dead	Juvenile	Sub-adult	Adult				
Green turtles (n = 251)	28.69 (72)	71.31 (179)	60.96 (153)	21.91 (55)	17.13 (43)	43.03 (108)	9.96 (25)	3.98 (10)	43.02 (108)
Hawksbill turtles (n = 71)	78.87 (56)	21.13 (15)	81.69 (58)	12.68 (9)	5.63 (4)	59.15 (42)	21.13 (15)	1.41 (1)	18.31 (13)
Olive ridley turtles (n = 11)	18.18 (2)	81.82 (9)	45.45 (5)	36.36 (4)	18.18 (2)	18.18 (2)	0.00 (0)	0.00 (0)	81.82 (9)
Leatherback turtles (n = 2)	0.00 (0)	100.00 (2)	100.00 (2)	0.00 (0)	0.00 (0)	0.00 (0)	0.00 (0)	0.00 (0)	100.00 (2)
Unidentified species	0.00 (0)	100.00 (3)	100.00 (3)	0.00 (0)	0.00 (0)	0.00 (0)	0.00 (0)	0.00 (0)	100.00 (3)
Total	38.46 (130)	61.54 (208)	65.38 (221)	20.12 (68)	14.50 (49)	44.97 (152)	11.83 (40)	3.25 (11)	39.94 (135)

3. RESULTS

3.1. Occurrence of stranded turtles

Between 2017 and 2020, 338 stranded turtles (130 live and 208 dead) were found along the shores of the Central Gulf of Thailand. The majority of stranded turtles were green turtles *Chelonia mydas* (74.26%, n = 251) and hawksbill turtles *Eretmochelys imbricata* (21.01%, n = 71); olive ridley turtles *Lepidochelys olivacea* (3.25%, n = 11) and leatherback turtles *Dermochelys coriacea* (0.59%, n = 2) were also found. Several carcasses could not be identified as a result of severe damage (0.88%, n = 3) (Table 1).

The life history stages of turtles are shown in Table 1; size ranges for each species are provided in Table 2. Most stranded sea turtles were juveniles (65.38%, n = 221), followed by sub-adults (20.12%, n = 68), and adults (14.50%, n = 49). Of 149 turtles whose sex could be determined, 120 were female (80.5%).

3.2. Causes of stranding

The possible causes of stranding (Table 1) were connected to macroplastics, health (infection), injury caused by boats, and unknown causes. For 203 stranded turtles for which a cause could be determined, macroplastics (entanglement or ingestion)

Table 2. Size of stranded sea turtles in the Central Gulf of Thailand from 2017–2020

Turtle species	Curved carapace length (cm)		Curved carapace width (cm)		Weight (kg)	
	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
Green	15–205	57.38 ± 11.13	10–98	51.20 ± 9.40	0.3–103	24.38 ± 13.89
Hawksbill	5.5–90	55.09 ± 14.34	5–85	49.61 ± 12.07	0.2–90	22.84 ± 15.23
Olive ridley	33–90	57.66 ± 13.71	36–69	51.87 ± 13.71	15–50	25.19 ± 17.25
Leatherback	30–83	49.45 ± 14.14	40–76	45.01 ± 12.65	8–53	16.71 ± 14.39

Table 3. Association between marine macroplastics and the viability of stranded sea turtles in the Central Gulf of Thailand from 2017–2020

Turtle species	Causes of stranding									Total	
	% Entanglement (n)			% Ingestion (n)			% Both (n)			% Live (n)	% Dead (n)
	Live	Dead	Total	Live	Dead	Total	Live	Dead	Total		
Green (n = 108)	34.26 (37)	26.85 (29)	62.11 (66)	2.78 (3)	19.44 (21)	22.22 (24)	3.70 (4)	12.97 (14)	16.67 (18)	40.74 (44)	59.26 (64)
Hawksbill (n = 42)	73.81 (31)	16.67 (7)	90.48 (38)	0.00 (0)	9.52 (4)	9.52 (4)	0.00 (0)	0.00 (0)	0.00 (0)	73.81 (31)	26.19 (11)
Olive ridley (n = 2)	50.00 (1)	50.00 (1)	100.00 (2)	0.00 (0)	0.00 (0)	0.00 (0)	0.00 (0)	0.00 (0)	0.00 (0)	50.00 (1)	50.00 (1)
Total (n = 152)	45.40 (69)	24.34 (37)	69.74 (106)	1.97 (3)	16.45 (25)	18.42 (28)	2.63 (4)	9.21 (14)	11.84 (18)	50.00 (76)	50.00 (76)

were the leading cause (74.88%, n = 152), followed by health issues (infectious and non-infectious diseases) (19.70%, n = 40) or injuries caused by boats (5.42%, n = 11).

The details of 152 stranded sea turtles found with macroplastics are shown in Table 3. Green turtles were the species most commonly found with macroplastics (71.05%, n = 108) followed by hawksbill turtles (27.63%, n = 42), while macroplastics were rare in olive ridley turtles (1.32%, n = 2) and absent in leatherback turtles. When the total number of each species is considered (Table 1), the ratio of hawksbill turtles (59.15%, n = 42 of 71) detected with macroplastics was significantly higher ($\chi^2 = 5.15$, df = 1, p = 0.023) than the ratio of green turtles (43.03%, n = 108 of 251) and olive ridley turtles (18.18%, n = 2 of 11) ($\chi^2 = 4.88$, df = 1, p = 0.027).

Notably, the frequency of macroplastics association with stranding varied significantly among sea turtles ($\chi^2 = 12.97$, df = 2, p = 0.001). Entanglement (69.74%, n = 106) by plastic was significantly higher ($\chi^2 = 137.44$, df = 2, $p < 0.00001$) than ingestion (18.42%, n = 28) and both entanglement and ingestion at the same time (11.84%, n = 18) (Table 3). When compared between 2 key species, hawksbill turtles (90.48%, n = 38 of 42) were entangled by macroplastics more frequently ($\chi^2 = 12.26$, df = 1, p = 0.000462) than green turtles (62.11%, n = 66 of 108). The percentage of green turtles that had ingested plastic (22.22%, n = 24 of 108) was significantly higher that had ingested plastic ($\chi^2 = 4.09$, df = 1, p = 0.043) than for hawksbill turtles (9.52%, n = 4 of 42) (Table 3).

3.3. Association between macroplastics and the death of sea turtles

The association between macroplastics and sea turtle death is shown in Table 3. Half of the strandings due to macroplastics had resulted in death, and the proportion of dead green turtles (59.26%) was significantly higher than the proportion of dead hawksbill turtles ($\chi^2 = 48.52$, df = 2, $p < 0.001$). Interestingly, the survival rate of sea turtles entangled in macroplastics was significantly higher (65.09%, n = 69 of 106) than for those that had ingested plastics (10.71%, n = 3 of 28) ($\chi^2 = 26.34$, df = 1, $p < 0.00001$). Some turtles ingested plastics and survived, and the macroplastic was excreted with faeces (n = 7) during rehabilitation at the rescue centre.

Necropsy examinations of all deceased turtles (n = 208) revealed that macroplastics were detected in the GI tracts of 46 turtles (22.11%) (Table 3). All turtles that ingested plastic showed signs of obstruction of the GI tract (stomach and small intestine) caused by a large mass of macroplastics. Of the 4 species, only green and hawksbill turtles consumed macroplastics.

3.4. Types of macroplastics found in the GI tracts and on the beaches

The types of macroplastics determined by macroscopic and microscopic examination are shown in Table 4 and Fig. 2. Macroplastics found in the GI

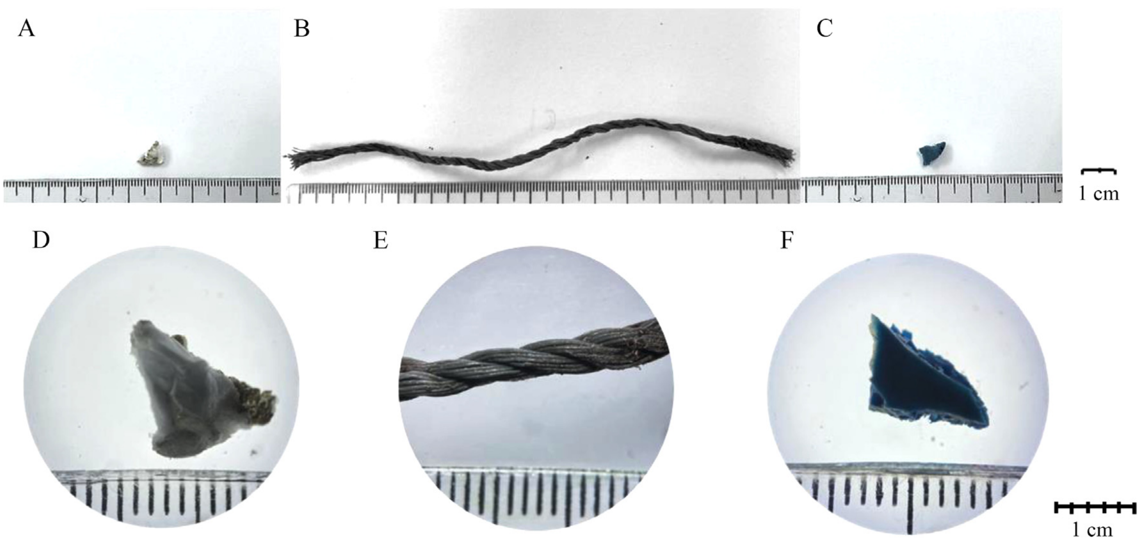


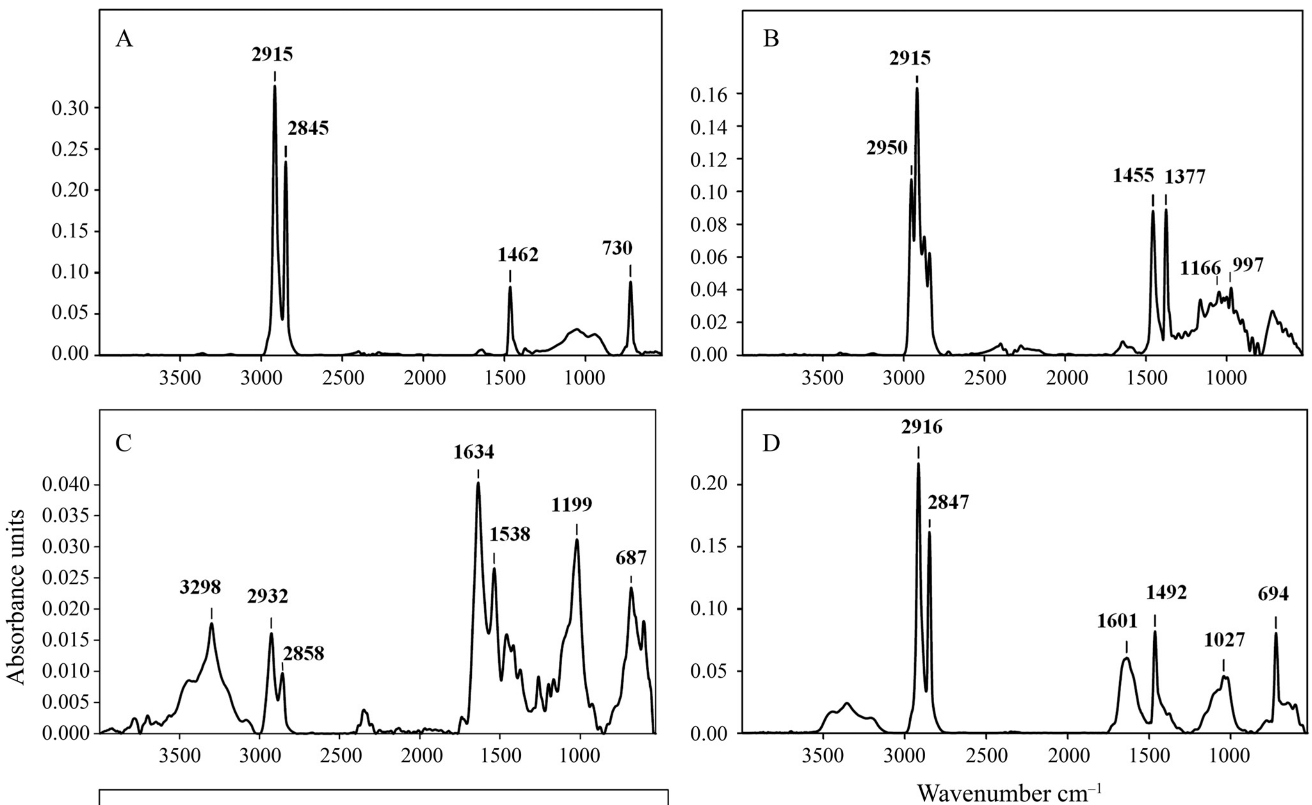
Fig. 2. Plastic debris showing (A) macroscopic and (B) microscopic appearance. Microscopic structure of plastic debris was identified using a stereomicroscope. Plastics were identified as (A,D) foam, (B,E) fibre (identified as part of a fishing net), and (C,F) hard plastic

Table 4. Type of plastic found in the gastrointestinal tract of 30 deceased turtles and on 13 beaches in the Central Gulf of Thailand between 2019 and 2020. n: number of plastic items collected

Source	Total no. of plastic items	Macroplastics % (n)				
		Fibre	Bags	Foam	Straw	Hard plastics
Turtles	244	62.30 (152)	29.51 (72)	0.81 (2)	0.41 (1)	6.97 (17)
Beaches	115	64.35 (74)	20.00 (23)	6.95 (8)	0 (0)	8.69 (10)

tract and on the beach were classified as fishing fibre, bags, foam, straws and hard plastics. The presence of plastic fibre in the turtles' GI tracts (62.30 %, n = 152 of 244) was significantly higher than other types of plastics (χ^2 = 426.09, df = 4, p < 0.00001). Similar to the GI tract, plastic fibre was also found on the beaches more frequently (64.35 %, n = 74 of 115) than other types of plastic (χ^2 = 132.76, df = 3, p < 0.00001).

The FTIR-derived signatures of each plastic found on the beaches and in the turtles' GI tracts are shown in Fig. 3. Composition analysis revealed that macroplastics in the GI tract (n = 244) were made from polyethylene (PE) (46.72 %, n = 114), polypropylene (PP) (40.98 %, n = 100), a copolymer of PE+PP (0.82 %, n = 2), or nylon (11.48 %, n = 28) (Fig. 4). Macroplastics found on the beach (n = 115) were made of PE (64.35 %, n = 74), PP (17.39 %, n = 20), PE+PP (6.96 %, n = 8), nylon (8.70 %, n =10), or polystyrene (PS) (2.61 %, n = 3). The propor-



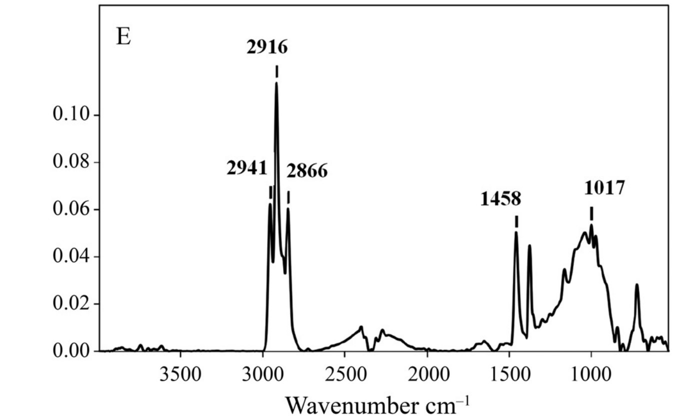


Fig. 3. Signature of each macroplastic analysed by Fourier-transform infrared spectrometry. Each plastic has unique absorbance bands. (A) Polyethylene absorbance bands are located at 2915, 2845, 1462, and 730 cm^{-1}. (B) Polypropylene absorbance bands are located at 2950, 2915, 1455, 1377, 1166, and 997 cm^{-1}. (C) Nylon absorbance bands are located at 3298, 2932, 2858, 1634, 1538, 1199, and 687 cm^{-1}. (D) Polystyrene absorbance bands are located at 2916, 2847, 1601, 1492, 1027, and 694 cm^{-1}. (E) Absorbance bands of a copolymer of polyethylene and polypropylene are located at 2941, 2916, 2866, 1458, and 1017 cm^{-1}

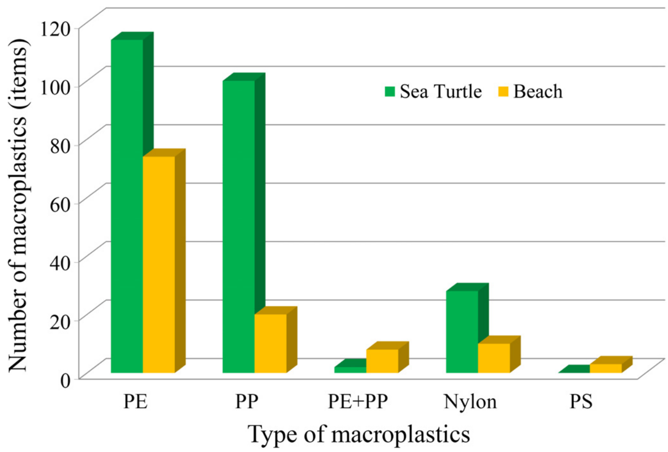


Fig. 4. Type of macroplastics found in the gastrointestinal tracts of sea turtles (n = 244) and on the beaches (n = 115). The composition of plastics was determined using Fourier-transform infrared spectrometry. Polyethylene (PE) and polypropylene (PP) were the most frequently observed plastics in turtles and on the beaches. Nylon, copolymer (PE+PP), and polystyrene (PS) were rare

tion of macroplastics made of PE was significantly higher than that of other materials from both the GI tract (χ^2 = 194.53, df = 3, p < 0.00001) and the beaches (χ^2 = 185, df = 4, p < 0.00001).

Generally speaking, fishing fibre can be from a fishing net or fishing line. According to FTIR analysis with the reference plastics, fishing nets were made of PP and/or PE, whereas fishing lines were only made of nylon. In the present study, most of the fishing fibres found in the turtles' GI tracts (n =152) were made of PE (56.58 %, n = 86), PP (26.32 %, n = 40), or nylon (17.11 %, n = 26). Fishing fibres found on the beaches (n = 74) were mainly made of PE (81.08 %, n = 60), PP (10.81 %, n = 8), or nylon (8.11 %, n = 6). There was a significant difference in the type of plastic fibres found in the GI tracts (χ^2 = 131.57, df = 1, p < 0.00001) and on the beaches (χ^2 = 103.89, df = 1, p < 0.0001). Therefore, fishing nets comprise the majority of plastic fibres found in the GI tracts (82.89 %, n = 126 of 152) and on the beaches (91.89 %, n = 68 of 74).

3.5. Association between macroplastics and life history stages of green and hawksbill turtles

The association of macroplastics with specific life history stages of stranded sea turtles is shown in Table 5. Of 3 stages, only the juvenile stage (n = 131) demonstrated a significant correlation with macroplastics (χ^2 = 36.03, df = 1, p < 0.001). In both species, the juvenile (χ^2 = 76.50, df = 1, p < 0.00001) and sub-adult stages (χ^2 = 21.33, df = 1, p < 0.00001) had a significantly higher rate of entanglement than ingestion. Additionally, the percentage of entanglement in adult turtles was significantly lower than in juveniles (χ^2 = 7.20, df = 1 p = 0.0072) and sub-adults (χ^2 = 4.44, df = 1, p = 0.035). In both species, adult turtles had a significantly higher rate of plastic ingestion than juveniles (χ^2 = 5.596, df = 1 p = 0.0090).

4. DISCUSSION

In the present study, we found that the green turtle was the most frequently stranded sea turtle species in the Central Gulf of Thailand, accounting for approximately 74 % of the total, followed by the hawksbill turtle, which accounted for approximately 21 %. The high stranding rate of green turtles can be explained by green and hawksbill turtles being the first and second most abundant populations, respectively, whereas olive ridley turtles and leatherback turtles are rare (https://km.dmcr.go.th/c_6/d_2688).

Table 5. Association of macroplastics with life history stage of 2 major species of stranded sea turtles (green and hawksbill) in the Central Gulf of Thailand from 2017–2020. Presence of macroplastics: macroplastics found in the gut or entangling the body

Turtle species	Stage	Problems with macroplastics			Presence of macroplastics	
		% Entanglement (n)	% Ingestion (n)	% Both (n)	% Yes (n)	% No (n)
Green (n = 143)	Juvenile (n = 82)	64.62 (42)	20.00 (13)	18.38 (10)	79.7 (65)	20.73 (17)
	Sub-adult (n = 29)	65.22 (15)	13.04 (3)	21.74 (5)	79.31 (23)	20.69 (6)
	Adult (n = 32)	45.00 (9)	40.00 (8)	15.00 (3)	62.5 (20)	37.5 (12)
Hawksbill (n = 58)	Juvenile (n = 49)	91.66 (33)	8.33 (3)	0.00 (0)	73.47 (36)	26.53 (13)
	Sub-adult (n = 9)	83.33 (5)	16.67 (1)	0.00 (0)	66.67 (6)	33.33 (3)
	Adult (n = 0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Both (n = 201)	Juvenile (n = 131)	74.26 (75)	15.84 (16)	9.90 (10)	77.1 (101)	22.90 (30)
	Sub-adult (n = 38)	68.97 (20)	13.79 (4)	17.24 (5)	76.20 (29)	23.68 (9)
	Adult (n = 32)	45.00 (9)	40.00 (8)	15.00 (3)	62.50 (20)	37.50 (12)

The incidence of macroplastic ingestion in the present study was highest in green turtles, followed by hawksbills. Comparing the 2 main species, entanglement was more prevalent in hawksbill than in green turtles, whereas a greater proportion of green turtles consumed macroplastics. This phenomenon can be explained by the feeding behaviour of these 2 species. Green turtles are primarily herbivores, usually consuming seagrass and seaweed (Carrión-Cortez et al. 2010, Awabdi et al. 2013, Stokes et al. 2019), the morphology of which is similar to the remnants of fishing nets and lines. Additionally, fishing nets and lines are more easily entangled on the rocky substratum where seaweed grows, and this may cause turtles to accidentally consume them (Thiel et al. 2018). In contrast, hawksbill turtles feed primarily on small animals such as fish, sponges, and algae (Meylan 1988, Leon & Bjorndal, 2002, Bell 2013). The plastic ingestion behaviour documented in this study is similar to that observed in other studies conducted in Brazil (González Carman et al. 2014, Rizzi et al. 2019). Due to the high incidence of entanglement in hawksbill turtles in this study, it is possible that the turtles attempted to capture small marine animals already entangled in the net, as the remnants of fishing nets are capable of trapping a large number of small marine animals (Sukhsangchan et al. 2020, Valderrama Ballesteros et al. 2018).

A related research project conducted on the eastern coast of the United Arab Emirates discovered that the majority of plastic found in the GI tracts of green turtles in that area was plastic fibre (Yaghmour et al. 2018). Conversely, studies in the Pacific Ocean found that most macroplastics found in the GI tract of green turtles near Hawaii were hard plastic items, whereas plastic fibre was rare (Wedemeyer-Strombel et al. 2015, Clukey et al. 2017). In the Gulf of Mexico, green turtles commonly ingest plastic sheets (e.g. shopping bags) rather than small pieces of hard plastic and plastic fibre (Choi et al. 2021). Notably, most macroplastics found in the present study were made of PE, a material similar to that found on the beaches, implying that turtles may consume the most abundant macroplastics in their feeding areas. These macroplastics that the turtles were entangled in or ingested are largely found close to the shore, as data from the Marine and Coastal Resources Research Centre revealed that turtles in the Gulf of Thailand rarely venture far from the shore (https://km.dmcr.go.th/c_6/d_982). Taken together, this suggests that the type of plastic found in the GI tracts of stranded sea turtles in each location represents the most abundant type of macroplastics found in the ocean or on the shore.

In the seas around Thailand, olive ridley and leatherback sea turtles are rare (https://km.dmcr.go.th/c_6/d_2688). They accounted for approximately 4% of the stranded turtles discovered in this study, and the primary cause of stranding was unknown (85%). Only 18% of olive ridley turtles were found entangled with macroplastics, while the standing of leatherback turtles was not associated with macroplastics. A study in the Southern Ocean of Brazil reported similar findings; olive ridley turtles had the lowest plastic ingestion rate among sea turtles (Rizzi et al. 2019). Conversely, studies in other areas have discovered a high incidence (up to 100%) of olive ridley turtles ingesting plastics (Wedemeyer-Strombel et al. 2015, Clukey et al. 2017, Jung et al. 2018b). For leatherback turtles, the occurrence of plastic ingestion is relatively low; one study revealed no incidence (Clukey et al. 2017) and another reported 34% (Mrosovsky et al. 2009). The most common form of plastic debris found in the GI tract of leatherback turtles is bags, which may imitate the main diet of leatherback turtles: gelatinous animals such as jellyfish (Mrosovsky et al. 2009, Heaslip et al. 2012).

The majority of known causes for the stranding of sea turtles in the Central Gulf of Thailand were entanglement by fishing nets (also known as ghost nets). This is not surprising, given Thailand's position as a leading exporter of edible fisheries products and the Central Gulf of Thailand's importance as a main area for fisheries according to data from FAO (https://www.fao.org/fishery/en/facp/tha?lang=en). Ghost nets are a global issue, as more than 500 000 t of fishing nets are lost and discarded annually, causing the entanglement of large marine animals, especially sea turtles (Wilcox et al. 2013). Some ghost nets can be tracked back to their country of origin, with the majority coming from Asian countries such as Thailand (Gunn et al. 2010). Another risk analysis study indicated that South-East Asia, particularly Thailand, might be one of the highest risk places for sea turtles to ingest plastics or become entangled (Schuyler et al. 2016, Duncan et al. 2017). Therefore, the elimination of ghost nets in the Gulf of Thailand should be the first priority for resolving the turtle stranding crisis. However, to date, no national legislation regulating ghost nets has been established, and few activities by government agencies, non-profit organizations, and local people to clear ghost nets from the ocean are reported by the media (https://www.diveagainstdebris.org/).

We discovered that most stranded sea turtles were juveniles, with the majority of these strandings associated with macroplastics and entanglement being more frequent than ingestion. This finding is consistent with previous studies in many areas, indicating that juvenile green and hawksbill turtles are more susceptible to entanglement than subsequent life stages (Duncan et al. 2017). Entangled animals, particularly smaller animals, are at risk of drowning if the fishing gear is very large or heavy. Additionally, they may perish from starvation and endure physical pain and illnesses as a result of the fishing gear cutting into their flesh (https://www.fisheries.noaa.gov/insight/entanglement-marine-life-risks-and-response).

The ingestion of plastic debris of sea turtles begins as soon as the turtles hatch (Eastman et al. 2020), and some studies suggest that juvenile turtles consume more plastic than other stages (Schuyler et al. 2016, Choi et al. 2021, Yaghmour et al. 2018). This finding is in contrast to our study, which discovered that adult sea turtles in the Central Gulf of Thailand consumed plastic at a higher rate than juveniles. The difference in plastic ingestion rates between turtles at different life history stages may represent their different feeding habits, which may be related to the abundance of different plants and plastics. The difference in plastic ingestion rates amongst turtles at various stages of development may reflect distinct feeding patterns connected to the presence of certain foods and plastic debris. We believe that the omnivorous adult green and hawkbill turtles might accidentally ingest plastics because they attempted to bite into large fishing nets to consume the food, particularly the tiny marine animals contained within the nets. Unlike adults, juvenile turtles are herbivorous and lack powerful beaks, which means they would be unable to damage the large fishing net and prefer to eat plants that are not covered by nets.

Nevertheless, juvenile turtles face a greater risk of death from plastic ingestion than adults because they consume a high quantity of plastic despite their smaller bodies (Wilcox et al. 2018, Choi et al. 2021). Consuming an excessive amount of macroplastics can obstruct the GI tract and result in death (Stamper et al. 2009), while a small amount of plastic ingestion can have sub-lethal effects through increasing satiety, inhibiting digestion, and impairing absorption, resulting in malnutrition and weakness (Santos et al. 2020). Notably, due to their inability to be degraded by digestive juice, both conventional and biodegradable plastics are toxic to turtles (Müller et al. 2012).

In conclusion, this study proposes that macroplastics, mainly fishing nets made of PE and PP, constitute a significant cause of the stranding of sea turtles in the Central Gulf of Thailand. These macroplastics may cause weakness, sickness, and eventually death in sea turtles, especially green and hawksbill turtles. Therefore, to prevent more sea turtle deaths in the Central Gulf of Thailand, it is critical to reduce or eliminate marine plastic debris, mainly fishing nets.

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