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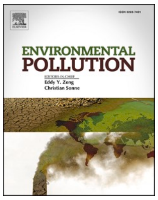

What type of plastic do sea turtles in Korean waters mainly ingest? Quantity, shape, color, size, polymer composition, and original usage

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ABSTRACT

Globally, sea turtles are at high risk of ingesting plastic. However, research on plastic ingestion by sea turtles in East Asia is scant, and no quantitative or qualitative investigation has been conducted in Korean waters. This study examined the plastic ingestion of sea turtles stranded, floating, or incidentally captured in Korean waters between 2012 and 2018. The quantity, shape, color, size, polymer type, and original usage of plastic debris (>1 mm) ingested by sea turtles were analyzed after being sorted from the gastrointestinal tracts of 34 turtles (21 loggerheads (*Caretta caretta*), 9 green turtles (*Chelonia mydas*), 2 leatherbacks (*Dermochelys coriacea*), and 2 olive ridleys (*Lepidochelys olivacea*)). The ingestion frequencies of greens, loggerheads, olive ridleys, and leatherbacks were 100%, 81%, 50%, and 50%, respectively. The mean amount of plastic ingested was 108 ± 253 mg/kg (38 ± 61 n/ind.). The ingested debris tended to be films and fibers (>80%), light in color (white and transparent; 65%), and light polymers (polyethylene, polypropylene, polypropylene [poly (ethylene:propylene)], expanded polystyrene; 93%). The original uses were identified for 187 pieces; single-use plastics (e.g., plastic bag and packaging) and fishing and aquaculture items (e.g., twine and net) were found to dominate. Green turtles (264 ± 433 mg/kg) ingested significantly higher amounts of plastic than loggerheads (72.8 ± 156 mg/kg). Green turtles ingested mostly fibers (51%), such as rope, twine, and net, while loggerheads ingested largely films (61%), such as plastic bags and packaging. Interspecies differences in quantities and shapes of ingested debris may be related to their distinct feeding habits and geographical range of movement. The present study demonstrates that sea turtles foraging in Korean waters are considerably affected by marine plastic debris, and indicates that proper waste management of single-use plastics and fishing gears is urgently needed to mitigate the damage that plastic debris causes to marine wildlife.

1. Introduction

Global production of plastics has steadily increased and amounted to 348 MMT in 2017 (PlasticsEurope, 2018). In 2015, roughly 79% of plastic waste was dumped in landfills or natural environments (Geyer et al., 2017). Jambeck et al. (2015) estimated that about 15–39% of improperly disposed plastic waste may enter the ocean annually. Plastics has been found as the most abundant type of marine debris on seafloor (41%; Pham et al., 2014) and beach (75%; SCBD, 2012). Unsurprisingly, over 80% of adverse environmental impacts on marine life are estimated to be associated with plastic debris (SCBD, 2012). To date, 914 species have been shown to interact with marine debris through physical entanglement or ingestion (Kühn and van Franeker, 2020). According to Kühn and van Franeker (2020), the first report of ingestion of marine debris was in a tiger shark (*Galeocerdo cuvier*) in 1931 (Gudger, 1949), followed by Leach's storm petrels (*Oceanodroma leucorhoa*) in 1962 (Rothstein, 1973). If marine organisms ingest debris, blockage of the gastrointestinal tract (GIT) may occur, resulting in malnutrition due to dietary dilution or even mortality (Kühn et al., 2015; Nelms et al., 2016).

Sea turtles have long been recognized as bio-indicators of marine debris pollution (Domènech et al., 2019; Matiddi et al., 2017). Seven species of sea turtles are known worldwide, all of which are affected by

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entanglement and ingestion (Kühn et al., 2015). Six are listed as "vulnerable to critically endangered", and one (Flatback, *Natator depressus*) as "data deficient", on the International Union for Conservation of Nature Red List (IUCN, 2021). Although there is no regular nesting site in Korea, sea turtles reached the East Asian coast from a wide nesting sites of loggerheads in Japan, and greens in Japan, Hong Kong, and Taiwan (MTSG report, 2020). In East Asian waters, loggerheads released from Japan have been found to reach East China Sea, or Hawaii across the Pacific Ocean (Hatase et al., 2002; Mansfield and Putman, 2013). Green turtles (*Chelonia mydas*) released from Jeju, migrated to Japan or to East China Sea identified from satellite tracking (Jang et al., 2018; Moon et al., 2011). Not much is known about the movement of leatherback turtles (*Dermochelys coriacea*) and olive ridley turtles (*Lepidochelys olivacea*), but one post-nesting female leatherback from Indonesia Papua was spotted in Korean waters by satellite telemetry (IOSEA report, 2012). For whole life stage, loggerheads, olive ridleys, leatherbacks are omnivorous, but greens undergo diet shift from omnivore to herbivore (Bolten, 2003). Of these, green turtles and loggerhead turtles rank among the six marine species with the highest frequency of occurrence (%FO) of plastic entanglement or ingestion (SCBD, 2012). It is estimated that 52% of global sea turtles have ingested plastic debris (Schuyler et al., 2016). Sea turtles' higher risk of plastic ingestion relative to other marine species may be attributable to the keratinized papillae in their esophagus, inhibiting the regurgitation of debris (Müller et al., 2012). For these reasons, the Marine Strategy Framework Directive (MSFD) adopted loggerhead turtles as an indicator species of plastic pollution in European seas (Hanke et al., 2013).

However, knowledge of the impact of plastic debris on sea turtles in the Northwest (NW) Pacific Ocean (including East Asian waters) is deficient. A database provided by a recent review paper (Lynch, 2018) presented that studies were conducted the most in the SW Atlantic (n = 27, 18%) followed by the NW Atlantic Ocean (n = 23, 15%) and Mediterranean (n = 16, 11%). By contrast, only five studies were conducted in East Asia, i.e., Japan (n = 3), China (n = 1), and the Philippines (n = 1), but there was no literature from Korea. Considering that more than a quarter to half of plastic debris is emitted to the ocean from East Asia (Borrelle et al., 2020; Jambeck et al., 2015), the studies in this region constitute a deficiency.

Various types of information can be extracted from analyses of plastic debris, including shape, size, color, polymer type, number, weight, and original usage. Considering the diverse characteristics of large plastic debris pieces, the information recorded in existing studies is relatively limited. Most of the published literature recorded the shapes and colors of plastics, while only four studies recorded polymer type (Caron et al., 2018; Duncan et al., 2019a; Jung et al., 2018; Pham et al., 2017), three studies recorded size (Clukey et al., 2017; Digka et al., 2020; Duncan et al., 2019b), and one recorded size groups including micro- (300 μm–5 mm), meso- (5–25 mm), and macroplastics (>25 mm) (Digka et al., 2020). Santos et al. (2015) reported the sources and original uses of ingested debris. A quantity of ingested plastics can be presented in terms of number or weight. Recording both the number and weight of plastics makes it possible to analyze and compare plastic contamination in various ways, while only 11 studies recorded both the number and weight of debris (Camedda et al., 2014; Campani et al., 2013; Clukey et al., 2017; Digka et al., 2020; Domènech et al., 2019; Duncan et al., 2019b; Lazar and Gracan, 2011; Matiddi et al., 2017; Poli et al., 2015; Schuyler et al., 2012; Yaghmour et al., 2018).

To bridge the gap in knowledge with respect to the NW Pacific region, we assessed sea turtles' exposure to plastic debris using stranded, floating, or bycaught carcasses from Korean waters. During the assessment, particular care was taken to extract all available information on plastic debris ingested by the sea turtles. We measured the mass and number of each plastic item to describe its abundance both in terms of number and mass, and then assessed its characteristics, including length, width, thickness, shape, color, original usage, and polymer type. Based on these data, we compared species-specific plastic ingestion profiles and identified the plastic types that pose the greatest threat to sea turtles.

2. Materials and methods

2.1. Sample and data collection

The present study was conducted using sea turtle carcasses stored at the National Marine Biodiversity Institute (MABIK), Korea. Dead sea turtles found were reported to MABIK, and their discovery status (stranded on beach, bycaught in stationary nets, or floating on sea surface) were also informed. MABIK collected turtles in suitable condition for taxidermy or other scientific analyses, and stored them in a freezer. Before necropsy, veterinarians examined the body condition of sea turtles and classified to five code categories, "0: Alive or just died", "1: Fresh carcass", "2: Moderate decomposition", "3: Advanced decomposition", "4: Mummified carcass", through external examination (stage of skin decomposition and attachment of carapace to body, *etc.*) (Eckert et al., 1999; Poppi and Marchiori, 2013). Consequently, 12, 10, and 12 turtles were classified to Codes 1, 2, and 3, respectively.

Detailed sample information, including capture dates, discovery status (stranded, bycatch or floating), and the geographical locations in which the sea turtles were found, is presented in Table S1 and Fig. 1. A total of 34 sea turtles (21 loggerheads, 9 greens, 2 leatherbacks, and 2 olive ridleys) were collected between July 2012 and October 2018. The majority of the turtles (n = 29, 85%) were found after being stranded; three were bycaught, and two were afloat. Most turtles (n = 28) were collected from the eastern coast of Korea (Goseong, Sokcho, Yangyang, Gangneung, Samcheok, Yeongdeok, Pohang, Gyeongju, and Ulsan); in particular, 12 turtles were from Pohang. Four turtles were collected from Jeju Island, two from the southern coast (Busan), and two from the western coast (Taean) (Fig. 1). One of the 34 carcasses was found to have a satellite transmitter fixed to its carapace and an identification tag on its body. This 3-year-old turtle, which had been born in an aquarium, was released to the sea from Jeju Island on August 29, 2018, with a satellite transmitter and an identification tag attached, and was found dead on the coast of Busan on September 9, 2018.

The turtles were necropsied between June 2017 and March 2019.

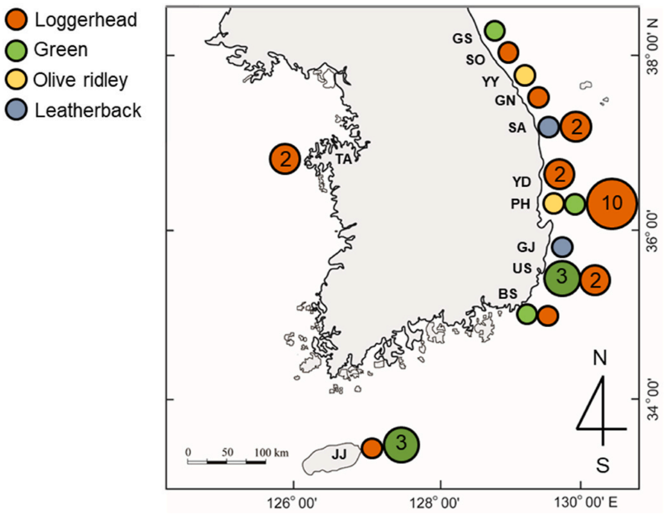

Fig. 1. Locations of stranded, bycaught, and floating sea turtles along the South Korean coastline in this study. If the turtle was found bycaught or floating, the location was defined based on the region where the fisherman's report was compiled. Numbers in circles are the number of individuals, and an empty circle denotes one individual. Loggerhead turtles (n = 21), green turtles (n = 9), olive ridley turtles (n = 2), and leatherback turtles (n = 2). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Prior to necropsy, each individual's biometric parameters—weight, sex, curved carapace length (CCL), straight carapace length (SCL), carapace width (SCW), plastron curved length and width, *etc.*—were measured. CCL is used as a representative parameter for age of sea turtles (Casale et al., 2011). During necropsy, each individual's plastron was incised, and the pectoral and pelvic musculature were removed. Subsequently, the organs and tissues were separated and sent for further studies (e.g., heavy metals, persistent organic pollutants, *etc.*). The GITs of the entire esophagus, stomach, and small and large intestines were isolated and cut. Large plastic-like items were then collected from the contents, and the remaining items were subsequently emptied onto 1 mm metal sieves. Food items in stomach content were also collected for diet analysis (Kim et al., 2021). Plastic-like items (>1 mm) were sampled with stainless steel tweezers. Moreover, biometric data of turtles and statistical analyses are provided in the Supporting Information.

The collected plastic-like items were washed with filtered tap water, wrapped in aluminum foil, and dried overnight in a freeze dryer (Gamma 1–16 LSC Plus; Martin Christ, Osterode am Harz, Germany). For each piece, color and shape (i.e., fragment, film, fiber, foam, or sphere) were recorded by two observers and double-checked each other to minimize observer bias. Bundle fibers were measured and recorded as single items if they were too tightly tied to unwind. It also were classified into three size classes, large microplastics (1–5 mm), mesoplastics (5–25 mm), and macroplastics (>25 mm) (GESAMP, 2019). The sources and origin objects of items were classified with reference to a national coastal debris monitoring card from the Marine Litter Integrated Information System (MOF and KOEM, 2017). Each item was weighed (to the nearest 0.0001 g), and its length, width, and thickness (to the nearest 0.01 mm) were measured using a stainless steel ruler, vernier calipers (500-182-30; Mitutoyo, Kanagawa, Japan), and micrometer (PK-1012CPX; Mitutoyo), depending on the item's size. After any detritus remaining on the surface had been removed using stainless steel tweezers, all plastic-like items were analyzed by Fourier transform-infrared spectroscopy (FT-IR; iS5; Thermo Scientific, Waltham, MA, USA) in attenuated total reflectance (ATR) mode, and the items identified as not plastic were removed from counting. Between each sample spectrum acquisition, the ATR crystal surface was cleaned with methanol. Spectra were analyzed manually, and spectral matching with a hit index ≥70% was considered acceptable.

3. Results

3.1. Quantity of ingested plastic debris

In total, 28 of the 34 turtles ingested plastic debris (82.4%). The %FO was highest in green turtles (100%), followed by loggerheads (81%), leatherbacks (50%), and olive ridleys (50%) (Table 1). A total of 1,280 pieces of plastic debris, corresponding to a total mass of 118.4 g, were found in the GITs of the turtles. The mean number of pieces of plastic per turtle was 38 ± 61 n/ind. (range: 0–229 n/ind.). The mean weight of plastics per turtle was 3,482 ± 4,495 mg/ind. (range: 0 − 15,602 mg/ind.), corresponding to 108 ± 253 mg/kg (range: 0 − 1,313 mg/kg). Regarding the size of plastic debris, the mean piece length per turtle was 70.9 ± 63 mm/ind. (range: 0–250 mm/ind.), the mean width was 16.4 ± 16.5 mm/ind. (range: 0–60.5 mm/ind.), and the mean thickness was 0.7 ± 1.1 mm/ind. (range: 0–4.6 mm/ind.) (Table S1).

The juvenile loggerhead turtle released from Jeju Island (AR 38) was found dead on the Busan coast (approximately 320 km in a straight line from the releasing site) after 11 days. Regrettably, its GIT contained abundant plastic debris (n = 221, 10.24 g), 693 mg/kg, and 244 mg/cm CCL (Figure S1). The ingestion rate of plastic debris can be calculated as 0.93 g/day and 20.1 n/day. This may be the first observation of how much plastic sea turtle can ingest during the known period at sea. A statistically significant negative correlation was identified between CCL and plastic ingestion quantity (mg/kg, n/ind.) (Pearson correlation test, $p < 0.05$), indicating smaller and younger turtles ingested more plastics.

Green turtles ingested the largest amount of plastics (264 ± 433 mg/kg, 76.4 ± 79.4 n/ind.), followed by loggerheads (72.8 ± 156 mg/kg, 28.1 ± 49.9 n/ind.), leatherbacks (0.7 ± 1.0 mg/kg, 1.0 ± 1.4 n/ind.), and olive ridleys (0.4 ± 0.5 mg/kg, 1.0 ± 1.4 n/ind.) (Fig. 2, Table 1). Green turtles ingested significantly more plastic than loggerheads at all concentration units: mg/ind., mg/kg, n/ind., mg/cm CCL, and mg/cm SCL (Wilcoxon rank sum test, $p < 0.04$). Leatherbacks and olive ridleys were excluded from all statistical analysis owing to their small sample size. Details of statistical analyses can be found in the Supporting Information.

3.2. Characteristics of ingested plastic debris

3.2.1. Color

Light-colored debris (white and transparent) was the most abundant (65%), followed by green (11%), mixed (11%), yellow (6%), black (3%), and others (each <3%) (Figure S2). White and transparent items accounted for over 60% of the ingested debris in all species. With respect to shape, fiber was the dominant shape of white and green items, while film was common in transparent, black, blue, red, and brown items. There was only one film gray item, and only one purple and one pink film item. For yellow and orange items, the fragment was dominant shape (Figure S2). Green turtles ingested significantly more white and green items than loggerheads (Wilcoxon rank sum test, $p < 0.002$) (Fig. 3, Table S2). While loggerheads ingested more transparent items than green items, the observed difference was not significant ($p > 0.05$).

3.2.2. Shape

Film was the most abundant shape of plastic debris in sea turtles (mass and number: 42% both), followed by fiber (mass and number: 39% both), foam (mass, 12%; number, 9%), and fragment (mass, 7%; number, 10%). Tangled fiber bundles constituted 37% by mass and 14% by the number of total fibers.

The most common colors for fragments were yellow (47%) and orange (20%), compared to white (49%) and green (26%) for fiber, transparent (50%) and white (26%) for film, and white (87%) for foam.

The top 3 most common polymer composition of each shape was as follows (Figure S3; Table S3): (1) for fragment items, nylon, polypropylene (PP), and polyethylene (PE) on both mass and number basis; (2) for foam items, PE, expanded polystyrene (EPS), and polyester on

Table 1
Amounts of plastic debris ingested by sea turtles collected from the Korean coast (%FO = frequency of occurrence, CCL = curved carapace length, SCL = straight carapace length).

Species	%FO	n/ind.	mg/ind.	mg/kg	mg/cm CCL	mg/cm SCL
Loggerhead (n = 21)	81	28.1 ± 49.9[a] (0–221)[b]	2,815 ± 4,147 (0–15,602)	72.8 ± 156 (0–693)	39.9 ± 65.7 (0–244)	39.6 ± 64.6 (0–226)
Green (n = 9)	100	76.4 ± 79.4 (1–229)	6,551 ± 4,772 (0–13,390)	264 ± 433 (0.1–1,313)	96.6 ± 88.1 (0–298)	107 ± 94.9 (0–300.9)
Olive ridley (n = 2)	50	1 ± 1.4 (0–2)	9.9 ± 13.9 (0–19.7)	0.4 ± 0.5 (0–0.7)	0.2 ± 0.2 (0–0.3)	0.2 ± 0.2 (0–0.3)
Leatherback (n = 2)	50	1 ± 1.4 (0–2)	136 ± 192 (0–272)	0.7 ± 1.0 (0–1.4)	1 ± 1.5 (0–2.1)	1.1 ± 1.6 (0–2.2)
Total	82	37.7 ± 60.5 (0–229)	3,482 ± 4,495 (0–15,602)	108 ± 253 (0–1,313)	50.3 ± 73.2 (0–298)	51.6 ± 76.3 (0–300.9)

[a] Average ± standard deviation.

[b] (min-max).

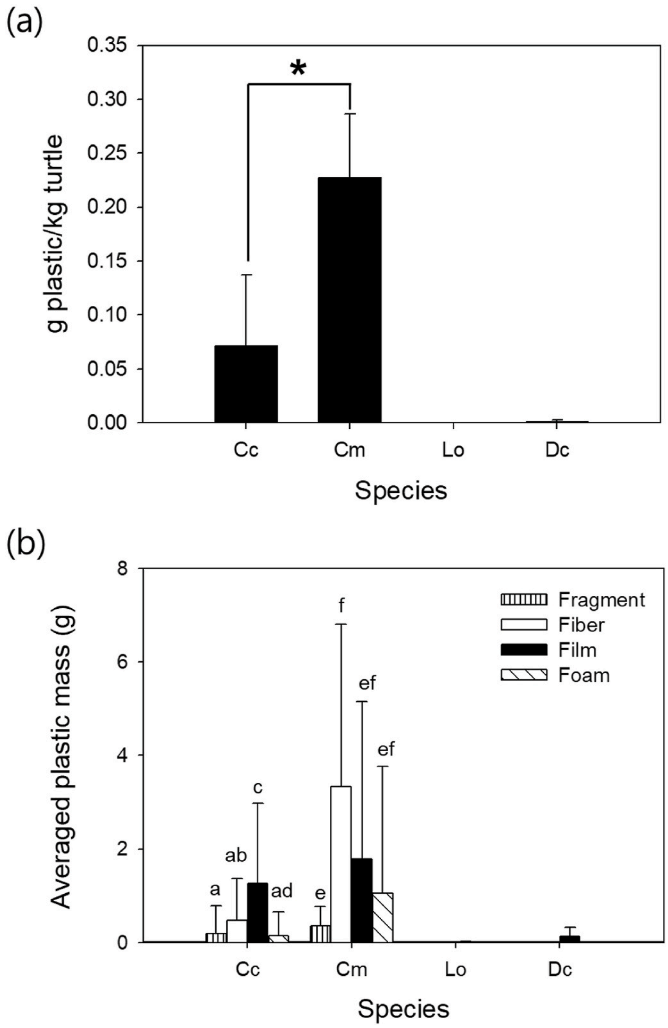

Fig. 2. Abundance of plastic ingested by sea turtles from Korean coastal waters (mean ± standard deviation) (a) and mean mass of plastic ingested by Korean coastal sea turtles, classified by shape (b). Asterisks on bars indicate significant differences between species. Different letters on bars indicate significant differences within species, with different letters used for loggerhead and green turtles (Wilcoxon rank sum tests, $p < 0.05$, Cc: loggerhead, Cm: green, Lo: olive ridley, Dc: leatherback turtles).

mass basis, and EPS, PE, and polyurethane on number basis. Contrary to the order for the weight-based metric, EPS preceded PE in number, which might be due to its friable nature; (3) for film items, PE, PP, and polyvinyl chloride (PVC) on mass and number basis; (4) for fiber items, polypropylene [poly (ethylene:propylene)] (iPP), PE, and PP on mass and number basis.

Green turtles predominantly ingested fibers (51%), followed by films, foams, and fragments, where the weight of fibers (3.33 g) was significantly higher than that of fragments (0.35 g) (Figs. 2 and 3, Wilcoxon rank sum test, $p < 0.05$). By contrast, loggerheads most frequently ingested films (61%), followed by fibers, fragments, and foams; films (1.26 g) were significantly heavier than the other debris shapes, and fragments (0.19 g) were significantly lighter (Figs. 2 and 3, Wilcoxon rank sum test, $p < 0.05$). Only one olive ridley and one leatherback ingested two films.

3.2.3. Polymer type

A total of 16 different polymer types were identified, of which polymers lighter than seawater (specific density = 1.02), such as PE (mass and number: 51% both), iPP (mass: 21%, number: 15%), PP (17%, 20%), and EPS (4%, 7%), comprised a large proportion in terms of weight or number (93%). However, heavy polymers, such as nylon (4%, 2%), polyester (2%, 1%), and others (2%, 4%), were also widely observed.

The most common shape for each polymer were as follows: films (54%) for PE; films (78%) for PP; mainly fibers (97%) for iPP; fibers (65%) for polyester; and fragments (66%) for nylon. All PS with the exception of EPS (foamed PS) were fragments. Macro-plastic was the most abundant size group (>25 mm, 63%) for each polymer, followed by meso- (5–25 mm, 31%) and micro- (1–5 mm, 6%), except for PS (mainly expanded form) (Figure S4).

The most common colors of each polymer in term of mass were white, transparent, and green (accounting for 84% of the total) for PE; transparent, and white (accounting for 66% of the total) for PP; white (65%) for iPP; white (68%) for EPS; yellow (71%) for nylon; and white (76%) for polyester.

Green turtles ingested 12 different polymer types of plastics, of which PE was dominant after iPP (Fig. 3). Meanwhile, loggerhead turtles ingested 14 different polymers, and PP was dominant after PE. Among the olive ridleys and leatherbacks, only one turtle of each species ingested two PE pieces.

3.2.4. Original usage of ingested plastic debris

Some plastic items were labeled with particular languages [9 items in Korean (2.19 g) and 10 items in Chinese (2.45 g)] (Fig. 4). Most were PP or PE, except for one piece of polyethylene vinyl acetate (PEVA) from China and one piece of iPP from Korea. We were able to identify the origins of 187 items based on text, material, or shape, including leaflets, plastic bags, packaging (filmed or foamed), water bottle labels, tape, rope, twine, fishing line, nets, gloves, and mesh bags. Among these, filmed packaging (19%), plastic bags (19%), twine (18%), net (16%), and rope (11%) predominated (Table S4).

The top 3 most common polymer weight compositions were as follows (Table S4): for plastic bags (n = 35), PE (97%), PP (1%), and polyester (1%); for filmed packaging (n = 36), PP (71%), PE (18%), and PVC (9%); for rope (n = 21), iPP (53%), PE (38%), and polyester (7%); for twine (n = 34), iPP (81%), PE (15%), and nylon (3%); for fishing line (n = 5), PE (57%) and nylon (43%); for nets (n = 29), PE (99%); for water bottle labels (n = 4), PP (100%); for a glove, PP; for a mesh bag, nylon; and for a leaflet, PE.

Green turtles mainly ingested fibers, including twine, net, and rope, while loggerheads primarily ingested films, such as filmed packaging, and plastic bags (Fig. 4). Yaghmour et al. (2018) also documented presumed sources of plastic debris from green turtles from UAE's coastal waters, with rope being the most abundant, and packaging showing the greatest mass.

4. Discussion

4.1. Relationship between body size and plastic ingestion

A statistically significant negative correlation was identified between CCL and plastic ingestion quantity (mg/kg, n/ind.) (Pearson correlation test, $p < 0.05$). This result indicates that younger turtles ingested more plastic debris. A similar trend emerged between the number of ingested plastics and size of sea turtles in Brazil (Rizzi et al., 2019); however, it was not applicable to Greek sea turtles (Digka et al., 2020). Schuyler et al. (2012) suggested that the quantity and type of ingested plastics may differ depending on the life cycle phase of sea turtles (i.e., young pelagic turtles *vs.* old benthic turtles), owing to their different diets and feeding styles. It is assumed that young pelagic turtles may be exposed to more floating debris, and more likely to ingest them. However, old benthic turtles which could dive deeper for longer duration may encounter floating debris less than younger turtles. Moreover, mature turtles have larger GIT diameters than younger turtles, making it easier for plastic to pass through (Bugoni et al., 2001). Previous study also

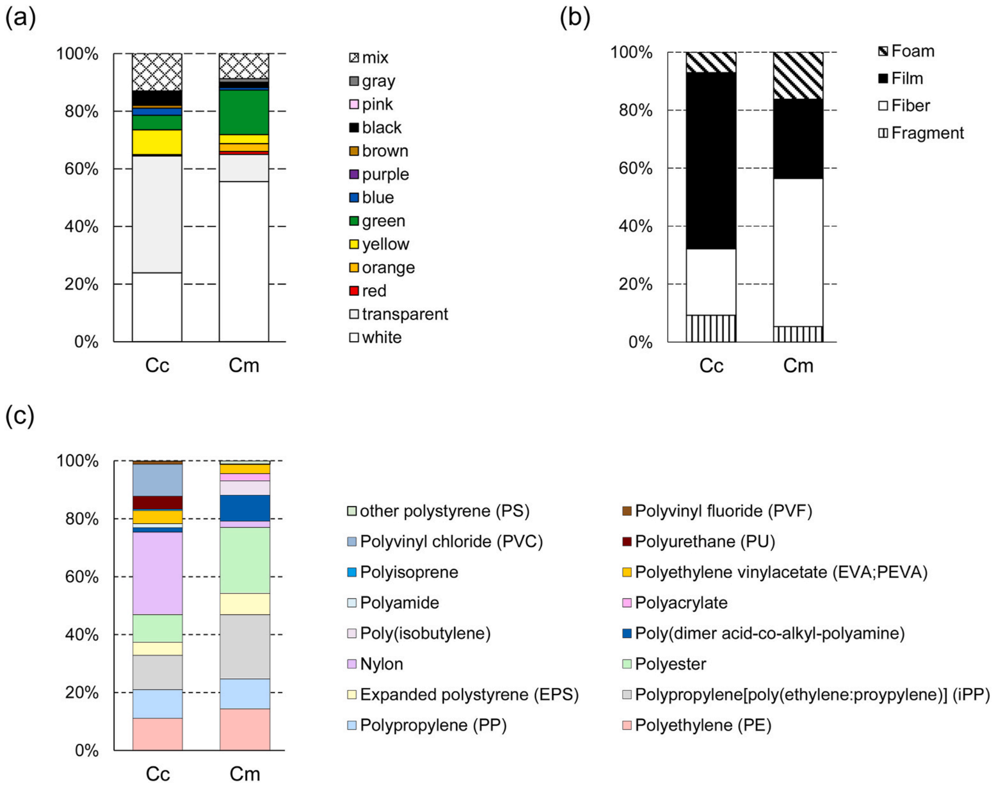

Fig. 3. Composition of debris color (a), shape (b), and polymer type (c) of ingested plastics from digestive tracts of loggerheads (Cc) and greens (Cm) based on total mass (A total mass of 70.11 g for 21 loggerheads, and 78.31 g for 9 greens.). Those from olive ridleys and leatherbacks were not presented in this graph due to limited sample sizes (number of turtles and amount of ingested plastics). . (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 4. Photographs of ingested plastic representing their original usage and written language.

reported that pelagic juvenile turtles ingest greater amounts of plastic debris than benthic adult turtles (Clukey et al., 2017). Since the body size of turtle may influence the ingestion quantity, it is more appropriate to compare the amount of ingested plastics between sea turtles of similar body size group from different regions. In addition, the released juvenile loggerhead turtle was found dead in 11 days. Given that this turtle was only 3 years old, the small diameter of its digestive tract would have rendered it more vulnerable to blockage by plastic debris.

4.2. Comparison with other regions: frequency of occurrence and amounts

The number of marine species negatively affected by the ingestion of marine debris, including seabirds, marine mammals, sea turtles, sea snakes, fish, and invertebrates, has increased from 331 in 2015 (Kühn et al., 2015) to 701 in 2019 (Kühn and van Franeker, 2020). Among marine wildlife, sea turtles have been most adversely affected by marine debris. According to a recent review by Kühn and van Franeker (2020), the %FO of plastic debris ingestion among sea turtles (32%) was higher than among seabirds (28%) and marine mammals (4%). The %FO value in this study (82%) is well above the global average for exposure of marine organisms to plastic debris (Kühn and van Franeker, 2020). The high detection frequency in recent studies may be attributable to the inclusion of small-sized plastics in GIT analysis. However, even when the mesoplastic (5–25 mm) and microplastic (1–5 mm) are excluded from the analysis, the %FO (76%) remains high. Plastic production in Korea (about 14 million tonnes) accounted for 4% of global production in 2020 (KPIA, 2021; PlasticsEurope, 2021). Korea was the second largest consumer of plastics (132.7 kg/capita) in 2015 (Euromap, 2016), and plastic consumption is steadily increasing. The mass production and consumption of plastics in Korea has led to an increase in the generation of plastic waste and its environmental emissions. To our knowledge, there is no study that scrutinized the pollution of marine plastic debris other than microplastic (Song et al., 2018) at sea surface and water column. However, it was estimated that 99,000 tons of debris entered the sea annually through Korean rivers (KMI, 2020). As 64–80% of floating debris in rivers were plastic, it can be estimated that about 63, 000–79,000 tons of debris are emitted to coastal waters annually. As discussed in section 4.4, the result of this study demonstrates that marine plastic debris from not only domestic but also foreign origins commonly affect sea turtles living in this sea area. Lebreton et al. (2017) estimated that a large amounts of plastic could be released from the Yangtze River in China (about 0.33 million tonnes), some of which is estimated to reach the Korean coast (Seo and Park, 2020). For loggerheads and greens, the high %FO in this study (81% and 100%, respectively) is consistent with earlier observations from Hong Kong and Japan (loggerhead, 85%; greens, 25–100%) (Fukuoka et al., 2016; Ng et al., 2016). The overall %FO for sea turtles in this study (82%) was higher than those from Mediterranean Sea (78%, Domènech et al., 2019), Caribbean Sea (5%, Barrios-Garrido et al., 2019), SW Pacific (63%, Godoy and Stockin, 2018), and SW Atlantic (57%, Rizzi et al., 2019; 43%, Rosolem Lima et al., 2018), but lower than NW Indian (86%, Yaghmour et al., 2018).

Lynch (2018) recommended debris mass per turtle mass (g/kg) as the optimal unit for evaluating ingestion quantity. Following her suggestion, the concentration unit was applied to the comparison of plastic ingestion levels between regions (Table S5). Loggerheads in this study (0.0728 g/kg) ingested less plastic debris than those from the Mediterranean Sea (0.094 g/kg, Domènech et al., 2019), and North Central Pacific (0.293 g/kg, Clukey et al., 2017). The green turtles in this study (0.264 g/kg) ingested less than those from North Central Pacific (1.74 g/kg, Clukey et al., 2017). In East Asian waters, loggerheads (0.0728 g/kg) and greens (0.264 g/kg) from Korean waters ingested fewer than those from Japanese waters (0.184 g/kg, 3.33 g/kg, Fukuoka et al., 2016), but 19 times more than greens from the South China Sea (0.0137 g/kg, Ng et al., 2016) (Lynch, 2018). Korea, China, and Japan share the East Asian waters, but there is a large difference in plastic ingestion level of sea turtles between regions. This difference could come from the difference in local plastic contamination levels, the characteristics of turtle samples (e.g., discovery status, body condition, body size, *etc.*), and methods of plastic analysis (e.g., size range, chemical identification, *etc.*). However, to date, dataset established in the East Asian waters is too limited to compare plastic ingestion levels across regions. To establish inter-comparable data, it is necessary to establish a standardized protocol for the assessment of plastic ingestion in sea turtle. In the world's ocean including Korean waters, the NW and Central Pacific regions showed the highest level of plastic ingestion (Lynch, 2018). This is likely due to the effect of the garbage patches formed by the North Pacific Subtropical Gyre (the "Western Garbage Patch" in the east of Japan and "Eastern Garbage Patch" in the Central Pacific between Hawaii and California) (Howell et al., 2012). Abundant plastic debris originating from Asia are thought to be introduced to the Eastern Garbage Patch (i.e., the Great Pacific Garbage Patch) by the Kuroshio Extension (KE) current system (Lebreton et al., 2018), and Asian rivers account for 86% of the total global riverine plastic emission to the ocean (Lebreton et al., 2017). Similar to sea turtles, despite the limited data available for other organisms in East Asian waters, marine organisms inhabiting this region (adjacent to the NW Pacific region) were exposed to significant amounts of plastic debris. For example, 56 pieces were found in four of nine seabirds (*Sula sula*, *Numenius phaeopus*, and *Pluvialis fulva*) from China (Zhu et al., 2019), while 2,978 pieces were found in 159 Swinhoe's storm petrels (*Hydrobates monorhis*), 9 pieces in 70 black-tailed gulls, and 45 pieces in a fin whale (*Balaenoptera physalus*) from Korea (Im et al., 2020; Nam et al., 2021).

Despite variations and deficiencies in the data, both the quantity and %FO of plastic debris are high in sea turtles from East Asian seas, including Korea. Earlier studies of the regional management unit, nesting site, and post-nesting migratory route have shown that sea turtles are widespread in the East Asian region (IOSEA report, 2012; MTSG report, 2020; Wallace et al., 2010). Although a large quantity of mismanaged plastic waste is generated and discharged into the ocean around East Asia, research on the ecological impact of marine plastic debris in this region is limited compared to America and Europe. Further research on the levels of exposure to marine plastic debris and its integrative ecological impacts in East Asian waters is warranted.

4.3. Interspecies differences

Green turtles (0.2638 g/kg) ingested 3.6 times more debris than loggerheads (0.0728 g/kg) in this study. In Japanese waters, green turtles (3.33 g/kg) ingested 18 times more than loggerhead turtles (0.184 g/kg) (Fukuoka et al., 2016). Casale et al. (2016) also showed that the mortality associated with debris ingestion was significantly higher in green turtles (10%) than loggerhead turtles (2%). In terms of shape, green turtles ingested more fibers, including twines and ropes, while loggerhead turtles ingested more films, including filmed packaging and plastic bags (Fig. 4).

The quantities and characteristics of plastics ingested by sea turtles may be related to diet and geographical range of movement. Adult green turtles forage on seagrass, algae, and invertebrates. On the other hand, loggerheads consume fishes, crabs, algae, *etc.* (Bolten, 2003). The diet analysis of sea turtles (including individuals in this study) from Korean coasts (Kim et al., 2021) also corresponded to the results of previous studies. The kelp species and gulfweed were commonly observed in GIT of green turtles. Contrastingly, kelps, jellyfish, and crab were frequently found in GIT of loggerheads.

Green turtles are herbivorous, being more likely to accidently ingest plastics entangled with macroalgae (Di Beneditto and Awabdi, 2014), or trapped in seagrasses (Sanchez-Vidal et al., 2021). On the other hand, loggerhead turtles are omnivorous (or carnivorous), being less likely to encounter or ingest these debris stuck in prey than greens because they opportunistically forage on seagrasses or plants (Mansfield and Putman, 2013). Moreover, turtles may mistake certain plastic shapes for prey owing to their similarity (Fukuoka et al., 2016). Therefore, these differences in diet and habitat characteristics may impact the differences that green turtles ingested more frequently and large amount of plastic than loggerheads. Also, they might contribute to the difference that fiber accounted for most common shape of plastics in greens, and films in loggerheads.

Moreover, the movement of green turtles and loggerhead turtles in East Asian seas varied in satellite tracking studies. Post-nesting green females in this sea area used only Western Pacific (adjacent to Northeast Asia and Southeast Asia) as foraging areas (MTSG report, 2020). In contrast, female loggerheads released from Japan migrated across the Pacific Ocean and reach even north of Hawaii (Mansfield and Putman, 2013). Marine Bio Resource Information System (MBRIS, https://gis.mbris.kr/web/main.do#) displayed the routes of movement of turtles released from Korea with a satellite transmitter, which were born in artificial incubator or rescued at the Korean coastal waters. The loggerhead turtles used the coasts of Korea and China mainly, and some of them moved to the northern coast of Japan. Likewise, green turtles actively moved along the coast of these three countries. A few of them moved further south to Hong Kong and Vietnam (Figure S5). In various literatures, Southeast Asian rivers transport substantial plastics towards the ocean than other regions (Jambeck et al., 2015; van Calcar and van Emmerik, 2019). Higher frequency and amount of plastic in greens may be due to this difference in regional pollution level.

In terms of color, green turtles ingested more white and green items, while loggerheads ingested more transparent items. Also, iPP was major polymer type after PE in greens, whereas, PP was frequent after PE in loggerheads. Characteristics of plastics were not separated but linked together since certain origins of plastics were produced in certain shapes, colors or polymer types. Therefore, if the origins of plastic ingested by each species are different, the shape and the polymer type may be disparate, too. Depending on the shape, the transit time through gastrointestinal tract could varies. The toxic effects can be occur due to physical effects according to shape and chemical effects of raw materials (monomer, oligomer, *etc.*) and plastic additives. These studies are needed to understand the biological effects of marine plastic debris on marine life. Therefore, it is imperative to figure out what original usage of plastic debris is most observed in sea turtles as discussed in section 4.4.

In the Pacific Ocean, green turtles reportedly ingested more film and fishing line/rope than loggerheads (Clukey et al., 2017). The high proportion of fiber was similar to our study. In some regions, however, the characteristics of the plastics ingested by loggerheads or greens showed no similarity to ours. Green turtles stranded along the Brazilian coast commonly ingested film (41%), and fragments (44%), while loggerheads generally ingested fiber (57%) (Rizzi et al., 2019). Greens and loggerhead turtles from the Japanese coast predominantly ingested film (93% and 53%, respectively; Fukuoka et al., 2016). Korea and Japan share the same sea, but the findings were in opposition.

4.4. Sources of plastics ingested by sea turtles and their implications

Among the ingested plastics, 10 pieces had Chinese writing on them and 9 had Korean writing. According to an annual survey of a Korean beach debris monitoring program for 40 beaches nationwide (OSEAN, 2018), 98% of the debris (by number) on the beaches originated from Korea, compared to 1.9% from China and 0.1% from other countries. In brief, the proportion of plastics of foreign origin is relatively high in sea turtles compared to debris found on beaches. This suggests that the turtles used sea areas near Korea and China as foraging grounds or migratory pathways. In fact, satellite tracking routes showed that greens and loggerheads released from Korea and Japan actively used the Korean, Chinese and Japanese waters (Hatase et al., 2002; Jang et al., 2018; MBRIS, https://gis.mbris.kr/web/main.do#; Moon et al., 2011) (Figure S5). In addition, debris released from China can be moved to the Korean waters via ocean current, resulting in common occurrence of Chinese debris along the Korean coasts (Seo and Park, 2020). Consequently, they were ultimately affected by plastic debris that originated from both countries.

With respect to shape, films (including plastic bags, packaging, bottle labels, and tape) were the most abundant debris shapes found in sea turtles ($n = 484$, 43%), while this proportion was relatively small compared to that in beach debris ($n = 3,149$, 12%, OSEAN, 2018) (Table 2). This suggests that sea turtles preferentially ingest film compared to other shapes. Beach debris cannot be regarded to have fully reflected the environment encountered by sea turtles. Still, it was used as an alternative to compare between ingested debris and surrounding environment in several earlier studies under the circumstances of insufficient information on debris in water column and seabed (Duncan et al., 2019b; Santos et al., 2016; Schuyler et al., 2012). They suggested that sea turtles may selectively ingest the plastic debris that they encounter, because ingested plastic differs in shape composition from that on nearby beaches. Since sea turtles primarily use visual cues, they ingest plastic bags that resemble their prey, i.e., jellyfish (Schuyler et al., 2012). According to bio-logging data, a green turtle displayed similar swimming characteristics, such as swimming speed and heading angle, when it encountered a jellyfish and a plastic bag (Fukuoka et al., 2016). Meanwhile, fibers were frequently detected both in sea turtles (39%) and on beaches (20%). Sea turtles are more likely to encounter plastics floating on the sea surface, suspended in the water column, or on the ocean floor compared to plastics washed ashore. Therefore, to fully understand turtles' responses to plastic debris, environmental matrices that they commonly contact, such as water columns and seabeds, should be analyzed. It is essential to develop action plans aimed at protecting sea turtles from marine debris. However, information on marine plastic debris in water columns has hitherto been limited to microplastics (Eo et al., 2021; Song et al., 2018), and just one study for macro debris on seabed is available (Song et al., 2021).

Some of the plastic debris from sea turtles (this study) and coastal beaches (OSEAN, 2018) was classified herein as single-use plastic items, fishery- and aquaculture-related items, and others (Table 2). Among these, single-use and fishery-related items were abundant in both sea turtles (36% and 63%, respectively) and coastal beaches (38% and 32%, respectively). Plastic bags and packaging predominated among the ingested single-use items (Table S4). The abundance of single-use plastics in the environment, as well as sea turtles, may stem from their high use rates in human societies. It is estimated that 23.5 billion plastic bags and other single-use plastics (4.9 billion PET bottles, 3.3 billion plastic cups) are used annually in Korea (Greenpeace Korea, 2019). Unfortunately, no official statistics are available relating to mismanaged single-use plastic waste in Korea. The abundance of fishery-related debris, including net, rope, fishing line, and EPS buoys, in sea turtles and the environment may be attributable to aggressive fishing activities in the Western Pacific, including Korea. Marine fishery production in the NW and Central Western Pacific accounted for 33% (34,008,821 tonnes/year) of global production from 2005 to 2016 (FAO, 2018). South Korea accounted for 1.3% (1,377,343 tonnes/year) of global production and 6.3% of that for the NW Pacific. Hong et al. (2014) estimated that about 51% of Korean beach debris was fishery-related. A recent study on seabed debris around Korea reported that debris were mostly related to fishing activities (98%) (Song et al., 2021). Our observations confirm that plastic debris generated by vigorous fishing activity affects the marine environment and marine life therein. During fishing activity, rope, net, or twine may be fragmented, lost, or deliberately discarded into the ocean, becoming marine debris classified as abandoned, lost, or otherwise discarded fishing gear (ALDFG) (Macfadyen et al., 2009). ALDFG, with the exception of lost gear, contributes about 10% to the total volume of marine debris (Macfadyen et al., 2009). EPS is used as a building insulation material, as protective food packaging, and for aquaculture buoys (Block et al., 2017; Lee et al., 2015). In this study, meso-sized EPS (5–25 mm, 66%) was more abundant than macro-sized

Table 2
Numbers and proportions (%) of debris classified by original usage and shape from sea turtles and on Korean coastal beaches (OSEAN, 2018).

	Category	Ingested debris			Coastal beach debris		
		Original usage	n	%	Original usage	n	%
Original usage	Single use	packaging, plastic bag, tape, bottle label	95	51	bottle, lid, packaging, plastic bag, Styrofoam packaging	9141	38
	Fishery and aquaculture	net, rope, fishing line twine	89	48	rope, twine Styrofoam buoy	7770	32
	Others	mesh bag, leaflet, glove	3	1	other plastic	7486	31
	Origin Indistinguishable		869	–			
Shape	Film		483	42		3149	12
	Fiber		441	39		5468	21
	Fragment		113	10		6096	23
	Foam		102	9		4371	16
	Unknown		0	0		7486	28

EPS (>25 mm, 28%). This difference in size distribution may be related to the physicochemical properties of EPS. Song et al. (2017) reported that EPS had a higher fragmentation rate than PP and PE. EPS is easily fragmented compared to other hard plastics in the environment and rapidly lose the original shape. Besides, EPS is actively used as buoy for culturing oysters, mussels and sea squirts in Korea, resulting in the major marine debris item (Hong et al., 2014). If EPS foams (n = 81) are counted as fishery items in the origin analysis, the proportion of fishery-related plastics increases (Table 2). The large quantities of disposable and fishery-related items found in sea turtles and on beaches clearly indicate that a reduction in the production and consumption of single-use plastics and mishandled fishing gear is crucial to mitigate the damage of plastic debris to marine wildlife.

5. Conclusion

Marine debris continues to affect the ecosystem and environment. Sea turtles have been consistently shown to be affected by the ingestion of, and entanglement in, marine plastic debris. However, this study was the first to systematically quantify and characterize the plastic debris ingested by sea turtles from Korean waters. The amount of ingested plastic was presented as both weight and number metrics, facilitating comparison with existing data. Various features of the debris, such as shape, color, size, polymer type, and original usage, were also presented.

Including the results of this study, the overall %FO of plastic debris in sea turtles was higher than that of other marine organisms, particularly loggerheads and greens. We recommend these turtles as indicator species for plastic ingestion in Korean waters owing to their high %FO and sample availability. The ingested plastics in sea turtles were predominantly film, and light in color and light polymer. Interspecies differences in the characteristics and quantity of plastic debris were observed between the greens and loggerheads. These differences may derive from the species-specific feeding habits and plastic pollution characteristics of the seas that the turtles use for foraging and migration. Most importantly, single-use and fishery-related plastics were major items ingested by sea turtles, which indicates that waste management of these two types of plastics should be the top priority to effectively reduce the adverse impact of plastic debris on sea turtles. Further research is warranted to comprehensively assess the impacts of marine plastic debris in various size groups on marine organisms (covering low to high trophic levels), trophic transfer and their habitats (covering the water column to seafloor), and to understand the key cues that evoke responses of sea turtles to marine debris, with the aim of designing effective mitigation strategies.

Credit author statement

Yelim Moon: Formal analysis; Methodology; Investigation; Writing – original draft preparation and editing. Won Joon Shim: Conceptualization; Project administration; Funding acquisition. Gi Myung Han: Methodology; Investigation. Jongwook Jeong: Investigation. Youna Cho: Investigation; Il-Hun Kim: Resources; Min-Seop Kim: Resources; Funding acquisition. Hae-Rim Lee: Resources. Sang Hee Hong: Conceptualization; Methodology; Supervision; Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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