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ORIGINAL RESEARCH ARTICLE

Spatial heterogeneity of marine debris distribution on a tropical remote island shoreline

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ABSTRACT

BACKGROUND AND OBJECTIVES: Enggano Island is in the Indonesian Sea, bordering the Indian Ocean. Cross-border marine debris will be stranded in the coastal areas of this island. This study was carried out over a 12-month, from June 2021 to May 2022, to examine marine debris's spatial and temporal accumulation. This study intends to assess the degree of marine debris accumulation on Enggano Island's coast, given its location adjacent to the Indian Ocean.

METHODS: This study employed a survey approach and was performed at 10 different stations in the southeastern part of Enggano Island. The first sampling was carried out 30 days after cleaning, during the lowest tide at the full moon phase (28 ± 3 days), conducted over 12 months from June 2021 to May 2022 to represent four seasons. For each category of marine debris, the abundance was determined by evaluating both the number of items and their respective weights. The relationship between seasonal abundance and the average seasonal current speed was examined to evaluate the influence of currents on marine debris levels.

FINDINGS: The total marine debris collected in this study was 16,382 items with a cumulative weight of 24,826 grams. The average density of marine debris was determined to be 0.387 ± 0.006 items per square meter, and the corresponding average weight was 11.545 ± 0.146 grams per square meter. Plastic has the highest percentage of all square meter's categories in all locations and seasons, namely 91.55 percent to 92.54 percent. In all categories of macro-debris, the most prevalent types of debris are Styrofoam, plastic bottles, fragments of plastic rope or small nets, thin plastic wrapping, and Plastic cups. The Marine debris found during the cleaning was plastic bottles from China, Switzerland, Sri Lanka, India, the Maldives, Myanmar, Malaysia, Singapore, Thailand, the Philippines, Australia, Seychelles, and the Middle East, with an average percentage of Indonesian-brand bottles (58.12 percent), foreign-brand bottles (19.59 percent), and unrecognized brands (22.29 percent). Moreover, substantial discrepancies in the abundance and weight of marine debris were recorded between various locations and seasonal periods throughout the sampling.

CONCLUSION: The marine debris that washed ashore on Enggano Island during the 12-month observation period, from June 2021 to May 2022, showed significant spatiotemporal variations. Each season was affected by variations in marine debris accumulation across different stations, along with the direction and speed of the seasonal currents. Plastic is the category of marine debris with the highest percentage in all locations and seasons, specifically 91.55–92.54 percent. It is believed that global marine hydrodynamics significantly contributes to marine debris strandings, indicating a need for more in-depth studies to understand the impact of hydrodynamics on the sources and heights of these strandings, especially for debris outside Enggano Island.

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INTRODCTION

Marine debris (MD) is the trash that enters or is released into the coastal or marine environment. Much like other pollutants, MD affects the habitat, ecological dynamics, and health of species, along with the ecosystems where it accumulates. If not carefully managed, any manufactured object that does not break down spontaneously in a matter of days or months has the potential to become MD. The majority of scrap materials consist of paper, wood, textiles, metal, glass, ceramics, rubber, and plastic (UNEP, 2005). Representing the most common type of MD, plastic waste is found in concentrations of 60 to 90 percent (%) along coastlines and almost 90 percent on both the surface and the ocean floor (Cózar *et al.,* 2014; Martin, 2013). According to estimates made by Jambeck *et al.* (2015) in 2010, between 4.8 and 12.7 million metric tons (MMT) of plastic waste - out of the 275 MMT produced in 192 coastal countries - entered the ocean. If the trend of trash generation continues without any advances in waste management, this quantity is predicted to rise to 14.8-16.3 MMT in 2016 and might reach 53-90 MMT in 2030 (Borrelle *et al.,* 2020). Low-middle-income (LMI) nations have set high aspirations for waste management, targeting a 50% recycling rate by 2030, a significant increase from the average of 21% recorded in 2016 (Borrelle *et al.,* 2020). By creating a National Action Plan (NAP) on Waste, Indonesia, one of the LMI nations, plans to cut waste by up to 70% by 2025 (Metadata Peraturan, 2018). The majority of plastic garbage originates from human activities (Woods *et al.,* 2019)., including fishing (Donohue, 2005; Unger and Harrison, 2016) and tourism (Hayati *et al.,* 2020; Kuo and Huang, 2014; Zhou *et al.,* 2011). In oceanic environments, plastic waste can be carried by surface currents, resulting in its distribution or concentration in certain locations (Zhang *et al.,* 2017). Even farther away from the actual source of the plastic debris, they can spread (Hardesty *et al.,* 2017). River estuaries, tides, waves, and currents are some of the elements that affect the amount of plastic that ends up on beaches, waterways, and sediments (Lo *et al.,* 2020; Zhang *et al.,* 2017). Seasonal variations play a crucial role in the accumulation of stranded marine debris, which can differ markedly in both spatial distribution and temporal patterns (Cheung *et al.,* 2016; Cordova *et al.,* 2022a; Mugilarasan *et al.,* 2021; Ryan and Perold, 2021; Suteja *et al.,* 2021; Thiel *et al.,* 2021). Plastic waste builds up in sediments (Mauludy *et al.,* 2019; Peng *et al.,* 2018; Sari Dewi *et al.,* 2015; Nakajima *et al.,* 2021), on the water's surface (Hammer *et al.,* 2012; Reisser *et al.,* 2015; Lebreton *et al.,* 2019; Rothäusler *et al.,* 2019; Takarina *et al.,* 2022), and along coastlines (Behera *et al.,* 2021; Cordova *et al.,* 2022a). According to a number of studies, MD contamination harms the sea's ecosystems and biota, among other things (Kumar *et al.,* 2021; Derraik 2002). For instance, large plastic trash can entangle biota in turtles (Colferai *et al.,* 2017; Petry *et al.,* 2001; Vélez-Rubio *et al.,* 2018; Wilcox *et al.,* 2018) and marine mammals (Baulch and Perry, 2014; Brentano and Petry, 2020; Nurhasanah *et al.,* 2024; Basri *et al.,* 2024). Marine life that consumes plastic debris can occasionally suffer fatal consequences from misperceived satiety, ruptured stomachs, or obstructions within the digestive tract (Jacobsen *et al.,* 2010). According to Prokić *et al.* (2019), contamination with plastic particles can harm organisms in a number of ways, including immune system dysfunction, oxidative balance, energy metabolism, neurological damage, and histological damage. Continuous observation of MD contamination in the oceans is essential, given its significant and widespread impact (Ondara *et al.,* 2021). There is a scarcity of studies focusing on the volume, distribution, and consequences of plastic in Indonesia. As of right now, reports of MD buildup on Sumatra's west coast have come from Padang and Aceh (Cordova *et al.,* 2022a), Banda Aceh's Krueng Aceh river estuary (Ondara *et al.,* 2021), and Bengkulu's Kualo Beaches (Johan *et al.,* 2020). Despite the substantial influx of plastic waste each year to the outlying islands of the Indian Ocean (IO), such as Enggano Island, there has been no research undertaken in these regions (Pattiaratchi *et al.,* 2022). Because seasonal variations will alter existing patterns, the seasons have an impact on the buildup and dispersion of garbage in the oceans and along the coast. The majority of the garbage that comes from the southern region of Indonesia will go westward into the Indian Ocean on ocean currents and monsoon winds, according to Purba *et al.* (2021). Furthermore, Rahmania *et al.* (2021) indicate that during the west monsoon, marine debris entering Banten Bay can disperse further beyond the bay into the Sunda Strait. According to the findings of Rizal *et al.* (2021), drifters from Cisadane 1 are likely to

be confined to the southern Sunda Strait during the southwest monsoon due to the influence of the South Java Current (SJC), whereas they will move westward towards Madagascar during the northeast monsoon. Additionally, the research from Alamsyah *et al.* (2022) shows that there are differences in the types and amounts of waste in the west and east monsoon in Bone Bay which are caused by differences in current patterns in each season. The island of Enggano boasts rich ecosystems comprising coral reefs, seagrasses, and mangroves, which serve as habitats for numerous marine species that hold economic importance. These natural resources are vital for the economic well-being of the 4,112 inhabitants of the island (BPS, 2022). This island is one of the outer islands in Indonesia and is situated in the Indian Ocean. Based on previous work by Purba *et al.* (2021), they have mentioned that most of the islands in outer Indonesia are affected by marine debris from the Indonesian seas and surrounding seas. This island also became a remote island due to its location but has high biodiversity, as is common with small islands in Indonesia with their mega biodiversity (Suyadi *et al.,* 2021). It is essential to shield these different ecosystems from the infiltration of harmful substances, including MD, which can adversely affect their health and stability. Protecting this ecosystem from being damaged by MD pollution is necessary since, until now, waste disposal by the community has only been burned, stockpiled, or left in the environment, including trash that has been washed up on the beach, because there is no landfill on Enggano Island. Monitoring and managing waste on Enggano Island can be the first step taken. For a duration of 12 months, the monthly accumulation rate of MD was evaluated, beginning with the first sampling that took place 30 days after the initial cleaning. The study's initial hypothesis is that the amount of MDs stranded on the beach is correlated with the season. During certain seasons there is a higher buildup of MD, which is influenced by current patterns. The second hypothesis suggests that the influx of debris originating from the sea outweighs that from the mainland. This study marks the first of its kind to take place on the outermost islands of Indonesia that border the Indian Ocean, given that prior studies focused on MD monitoring have solely been conducted along the west coast of Sumatra Island. The concentration and distribution of MD, as well as the possible sources of stranded MD deposited in the study area, can be determined with the use of the study's findings. In addition, it will provide the groundwork for MD management initiatives at the regional level. Because Enggano Island borders the Indian Ocean, the purpose of this study is to determine whether the amount of MD buildup on its shore is extremely high. In 2022, this investigation was conducted on Indonesia's Enggano Island.

MATERIALS AND METHOD

Study area

This study took place in the Enggano Island area, one of Indonesia's foremost inhabited islands, which administratively belongs to the North Bengkulu district, Bengkulu Province (Fig. 1). Enggano Island has the closest distance to South Bengkulu Regency, which is 60 miles and 90 nautical miles from Bengkulu City. Enggano Island, with a land area of ± 39,720 hectares (ha) and a coastline length of ± 112 kilometers (km), has a population of 4,112 people in 2022, spread across six villages with six different tribes (BPS, 2022). The sampling took place at ten designated sites along the northern beaches of Enggano Island, which are situated near residential zones and display varying beach characteristics as defined by the National Oceanic and Atmospheric Administration (NOAA). The selected sites met several criteria: they featured either sandy or pebbly coastlines, provided access throughout the year or seasonally depending on conditions, lacked breakwaters or piers that might interfere with local water circulation and the accumulation of marine debris (MD), extended at least 100 meters (m) in length parallel to the shoreline, and were not subject to cleaning operations (Lippiatt *et al.,* 2013).

Sampling and debris estimation

The initial step in sampling was to clean the beach area which was the sampling location. Several MD found during cleaning came from outside Indonesia, the brand, printed language, and country of manufacturing mentioned were used to determine the country of origin, and debris in the form of products that were not available in Indonesia was classified as debris originating from outside Indonesia (Jang *et al.,* 2014; Lee *et al.,* 2012). In cases where the product's origin is not clearly indicated, one can resort to using Google for tracking purposes by

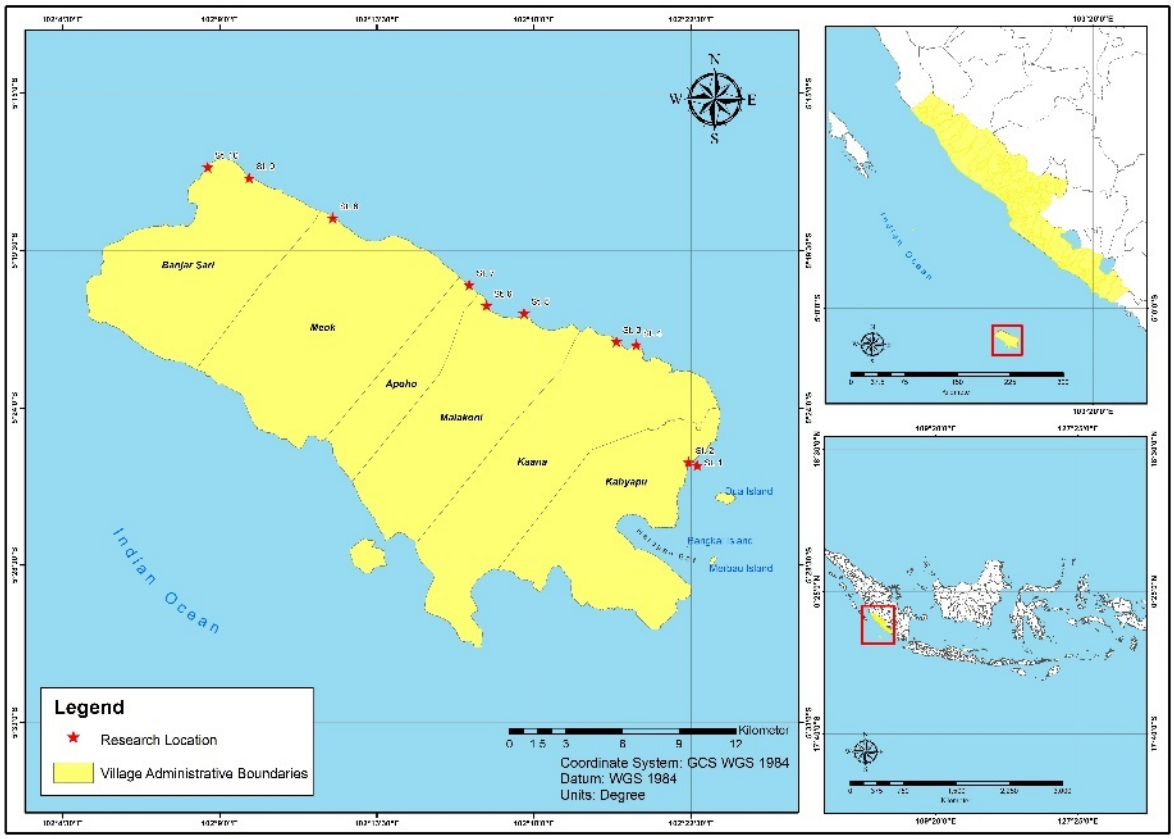

Fig. 1: Geographic location of the study area and sampling points in Enggano Island, Indonesia

analyzing the inscriptions on the bottle (bouwman *et al.,* 2016). After 30 days since the initial cleaning, MD samples were taken during the full moon every 28 (28 ± 3) days when the tide was low, between the highest and lowest tides to provide an accurate picture of the accumulation of plastic waste in that month. As noted by Lippiat *et al.* (2013), this sampling approach is effectively illustrating that collecting data at low tide during a full moon accurately reflects the amount of debris washed ashore during that month. The study was carried out over the course of one year to examine the seasonal representation. The 50 m line transect was divided into 2, with the width adjusted to the width of the beach at each sampling location so that the area of each location may be different. Each sampling location was equipped with Global positioning system (GPS) markers. The sampling process was conducted monthly, beginning in June 2021 and concluding in May 2022. MD that is collected and recorded must be at least 2.5 cm long, so it can be clearly visible and minimize the possibility of not being recorded. Debris that may be buried should be excavated and collected for recording. After being cleaned with water, the collected MD is wind-dried (slowly dried with air, away from direct sunlight) so that it can be visually identified, counted, and weighed using a digital scale (Digital Scales Harnic Heles HL-4350), maximum capacity of 5 kilograms (kg), accuracy of 0.1 gram (g), determined by the NOAA Program's categories, which include plastic and rubber, metal, glass, wood or paper, cloth, and others (Cordova and Nurhati, 2019; Lippiatt *et al.,* 2013). All identified MD types were employed to create distinct categories. Plastic and rubber were segmented into 13 sub-categories, whereas metal and fabric were each assigned one sub-category. Glass was categorized into two sub-categories, and processed wood was found only in certain sampling sites. Corpse/animal feces, leftover food, and unidentified waste are all classified as "other." Stranded MD density was calculated using

Eq. 1 (Cordova *et al.,* 2022a):

$$D = n / \omega \times l \quad (1)$$

Where,

D is debris density (items or weight per m^2); n is the item (number) or weight (g) of observed debris, ω is the transect width (m), and l is the transect length (m).

To determine the variation in abundance (number of items and weight) between seasons at each study location using statistical analysis non-parametric Kruskal Willis statistical test and Mann-Whitney paired post hoc test with a significant level of $p < 0.05$ using PAST (PAleontological STatistics) version 4.03 (PAST 4.03) for windows (Cordova *et al.,* 2022a; Hammer *et al.,* 2012). According to Triana *et al*. (2021) and Purba *et al*. (2021), seasonal changes are divided into three-month segments. They characterize the seasons as: the first transition or inter-monsoon period from March to May (MAM), the southeast monsoon from June to August (JJA), the second transition or inter-monsoon from September to November (SON), and the northwest monsoon from December to February (DJF).

The pattern of currents in four different seasons at the study location

The output model/monthly average data of current velocity in the direction-x (u) and the direction-y (v) in 2021 and 2022 of Enggano Island waters was downloaded from Copernicus Marine Service (CMS), taking into account the coordinates of the area, depth layer, time range, and the selected parameters. Subsequently, the data downloaded in the network common data form (netCDF) underwent additional processing software to derive average seasonal yields. In this study, the software used was PyFerret and ocean data view (ODV). The surface current system needs to be studied to see or predict the distribution of MD (Van Der Mheen *et al.,* 2020).

RESULTS AND DISCUSSION

The amount of MD during cleanup

In all observation stations, there were five sub-categories with the highest average number. The highest number of items was Styrofoam (0.138 ± 0.19 items/m^2), followed by plastic bottles (0.150 ± 0.25 items/m^2), plastic rope/small net piece (0.112 ± 0.19 items/m^2), thin plastic wrap (0.033 ± 0.03 items/m^2), and rope/fishing line/fishing rod (0.030 ± 0.03 items/m^2). The total MD collected at the time of cleaning from the 10 observation stations in this study was 2.268 items (5.77 tems/m^2), with a cumulative weight of 107,985.25 g as 274.65 grams per square meters (g/m^2). According to Table 1, the occurrence of plastic bottles is notably high at almost every station, with percentages falling between 11% and 32%. Station 10 is anticipated to exhibit the highest level, primarily due to the considerable volume of debris that has been stranded from the sea. In contrast, stations 1, 5, and 6 have a high percentage other than input from the sea, presumably because they are close to ports and fishery activities. The plastic rope/small net piece percentage is high at all stations except stations 1, 4, and 5. The greatest proportion of rope, fishing line, and fishing rods is observed at station 2, which can be attributed to its location near beaches that experience the most fishing activity. Conversely, Styrofoam was found in high amounts across all stations, except for station 2, where thin plastic wrap was the most abundant material. This Styrofoam mainly comes from fish storage boxes that are already in the form of fragments or shards. The percentage of debris weight differs from the percentage of the amount. For example, the weight percentage of plastic bottles is lower than the amount percentage at almost all stations because they weigh less. At stations 4 and 8, the weight percentage of rope, fishing line, and fishing rod is considerably greater than the total percentage, primarily because large net fishing gear was identified at these sites. This also holds true for apparel, shoes, sandals, and gloves; while the percentage may be lower, their weight percentage is significantly greater. Overall, it can be seen from the average percentage of MD at all stations (Table 1) that there are five sub-categories with the highest percentage. Styrofoam is the highest (23.41%), followed by plastic bottles (20.82%), plastic rope/small net piece (16.28%), thin plastic wrap (10.44%), and rope/fishing line/fishing rod (7.82%). While the average percentage of weight, there are six sub-categories, of which the highest is rope/fishing line/fishing rod (20.63%), followed by plastic bottles (13.48%), plastic rope/small net piece (13.38%), shoes/sandals/gloves (12.62%), glass bottles (12.27%), and Styrofoam (9.79%). The MD found during the cleaning included glass and plastic bottles originating from outside Enggano.

Table 1: Percentage of stranded MD during cleaning on Enggano Island from 22 categories based on abundance (A) and weight (W)

Category		I		II		III		IV		V		VI		VII		VIII		IX		X	
		A(%)	W(%)	A(%)	W(%)	A(%)	W(%)	A(%)	W(%)	A(%)	W(%)	A(%)	W(%)	A(%)	W %)	A(%)	W(%)	A(%)	W(%)	A(%)	W(%)
Plastic and Rubber	Ball, tire, balloon	0.46	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Plastic bottle	26.62	4.23	10.71	8.52	15.91	14.30	26.67	6.89	26.62	16.59	15.72	22.29	12.89	28.69	16.19	6.52	24.38	15.16	32.49	11.60
	Plastic cup	4.86	1.29	2.55	2.15	7.95	6.57	0.00	0.00	9.89	4.70	9.70	11.23	7.11	3.44	10.43	0.83	2.83	4.18	3.54	1.74
	Plastic cover	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.01	0.48	0.00	0.27	2.16	0.00	0.00	0.38	0.62	0.00
	Plastic match	0.00	0.00	2.04	0.73	1.14	0.24	10.00	3.49	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.29	0.00
	Thin plastic wrap	15.05	6.50	30.61	9.72	2.84	0.00	23.33	2.23	2.28	2.00	9.70	5.66	5.33	0.08	7.91	4.67	6.71	3.85	0.72	1.16
	Thick plastic wrap, sack	0.93	2.90	4.59	13.83	0.00	0.00	0.00	0.00	0.00	0.00	1.00	12.47	0.44	0.00	0.00	3.27	2.47	0.00	0.00	0.46
	Rubber band, rubber piece	0.69	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	1.06	0.00	0.00	0.00
	Straw	0.23	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.33	0.00	0.00	0.00	0.00	0.00	0.00	0.29
	Shoes, sandal, glove	3.94	8.62	2.55	2.24	9.09	23.48	0.00	0.00	10.27	22.23	5.35	0.00	12.44	23.17	8.63	8.09	5.30	19.87	8.33	18.55
	Styrofoam	17.13	2.53	1.02	1.25	29.55	10.19	26.67	4.46	33.27	10.36	15.05	12.21	32.44	13.98	14.03	9.50	39.93	14.14	25.02	19.29
	Rope, fishing line, fishing rod	11.57	22.69	24.49	19.32	9.09	5.93	13.33	82.93	7.60	5.80	5.02	4.95	0.00	2.57	0.00	62.09	5.30	0.00	1.82	0.00
	Plastic rope/small net piece	5.09	17.84	13.27	16.64	18.75	16.93	0.00	0.00	2.28	16.59	33.44	18.05	20.00	13.88	35.97	0.63	9.19	13.41	24.83	19.86
Metal	Can	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.00	1.00	4.07	0.89	0.00	1.08	0.00	0.00	2.34	0.00	0.31
Glass	Glass bottle	1.85	2.90	0.00	0.00	5.11	22.10	0.00	0.00	6.46	21.56	2.01	8.58	4.89	13.76	3.60	3.48	2.12	26.68	2.34	23.61
	Glass, broken glass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.95	0.16	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.57
Cloth/ Fiber	Clothes	11.57	29.60	8.16	25.60	0.57	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.84	0.71	0.00	0.00	2.56
Others	Others	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



Fig. 2: Foreign plastic bottles' brands found washed up on Enggano Island

The analysis of brand identity, language, and origin reveals that numerous bottles originate from China, Switzerland, Sri Lanka, India, the Maldives, Myanmar, Malaysia, Singapore, Thailand, the Philippines, Australia, Seychelles, and the Middle East (Fig. 2), with an average percentage of Indonesian brand bottles (58.12%), foreign brand bottles (19.59%), and unrecognized brand bottles (22.29%). No location at any sampling station has undergone cleaning, possibly due to the extensive buildup of debris from outside influences over the years. Brands from China, Indonesia, Thailand, India, Malaysia, Singapore, South Africa, and other countries were the source of MD on the Seychelles islands, according to a different study by Vogt-Vincent *et al.* (2023). The deposition of microplastics from remote areas, along with floating plastic debris, is affected by the monsoon winds, which integrate these materials into the regional current system. According to labels, the MD stranded on St. Brandon's Islands came from Malaysia, Thailand, and Indonesia, and it's possible that the South Equatorial Current of the Indian Ocean brought them to the archipelago, according to another study by Evans *et al.* (2011). Documentation reveals that most of the medical professionals who became stranded on the Little and Great Nicobar Islands were from adjacent nations, including China, Cuba, Indonesia, Malaysia, Myanmar, and Thailand rather than India (Das *et al.*, 2016).

Plastic has the highest percentage of all MD categories in all locations and seasons, namely 91.55% - 92.54%. Some MDs found are likely from ship traffic activities; in this study, MDs of drink bottles, both plastic and glass, with brands that may originate from cruise ships or ship waste in the past, were also found. As noted by Čulin and Bielić (2016), the origins of debris in marine environments include passenger ships, merchant ships, recreational vessels, commercial fishing boats, oil drilling platforms, and military vessels. Enggano itself is included in ALKI 1 (Indonesian Archipelagic Sea Channels). Despite the fact that ship debris disposal was forbidden by the 1988 International Convention for the Prevention of Pollution from Ships (MARPOL), it still occurs, one of which is through illegal disposal (Richardson *et al.*, 2021; Stelfox *et al.*, 2020). Historically, the primary source of plastic pollution in the oceans has been ships, which have a tradition of disposing of debris directly into the sea (Hagen, 1990). Furthermore, the MD material that washed up on the coast of Enggano Island might have been transported from different islands or countries, influenced by surface currents. According to Pattiaratchi *et al.* (2022), Van Der Mheen *et al.* (2020), and Purba *et al.* (2021), this current can

facilitate the movement of plastic waste to the Indian Ocean via the Indonesian Crossflow. Their research highlights that monsoon winds play a significant role in influencing the distribution of marine debris. Marine debris in the Sunda Strait expanded up to 938 kilometers to the west side of the strait and the Sumatra Island shore, according to the findings of tests conducted using GNOME (General NOAA Operational Modeling Environment). According to research by Akbar *et al*. (2022), which employed the same approach, the movement of waste is influenced by seasonal current patterns. Rizal *et al.* (2021) reported that the results of marine debris tracking by the mobidrift client portal (MDC) on the Cisadane 01 drifter were detected moving westward out of Indonesian territory, after floating on the ocean for over a year, they arrived at the east coast of Africa. According to research by Kisnarti *et al*. (2021), marine debris originating from six coastal cities was tracked using a trajectory model and a numerical model developed with the Hamburg Shelf Ocean Model (HAMSOM). The study demonstrated that these particles moved with ocean currents, dispersing to regions around the source of the waste and even reaching areas outside of Indonesian territorial waters. Duncan *et al.* (2020) reported that the movement of single pieces of plastic waste as 500 milliliters (mL) bottles of polyethylene terephthalate beverages) via the Ganges River system into the marine system Bay of Bengal was a 2,845 km maximum distance for 94 days. Cordova *et al.* (2022a) stated that many macro-debris objects remain afloat after They can travel great distances with ease and penetrate aquatic environments. The movement of ocean currents has led to the delivery of marine debris to the islands, where the south monsoon current (SEM) has contributed to the entrapment of debris in the Cocos (Keeling) Islands (Lavers *et al.,* 2019). Krishnakumar *et al.* (2020) argued that debris disposed of might be swept away by currents in the maritime environment, which would then circle the island before arriving in the Andaman and Nicobar Islands' coastal regions. he prevailing monsoon circulation will cause variations in surface currents (Sprintall *et al.,* 2009). Across all sampling locations, the marine debris found on the shores of Enggano Island is predominantly made up of plastic materials. This includes plastic bottles, lightweight plastic wraps, fragments of plastic ropes and nets, Styrofoam, and various fishing gear like ropes and lines (Fig. 3). Plastic bottles and thin plastic wrap probably originated from land as debris from daily human activities and from the sea as stranded debris. These types of plastic have high buoyancy and are widely used as disposable food and beverage packaging. From 12 billion in 2000 to 36 billion in 2006, the amount of waste produced by plastic bottles is substantial and still rising (Ajaj *et al.,* 2022). For instance, PET water bottles are commonly used in the United Arab Emirates (UAE), where each person may use up to 450 bottles of water year. In contrast, water bottles made of polyethylene terephthalate (PET) are a huge waste and have a considerable carbon footprint (Ajaj *et al.,* 2022). The elevated levels of Styrofoam and fishing gear, including rope and fishing line, are probably a result of fishing activities, as Styrofoam is commonly utilized by fishermen to store their catches. When it is damaged and cannot be used, it will be thrown into the sea and washed up on the coast as fragments or debris. In studies focused on the abundance, distribution, and sources of microplastics in the northern regions of the South China Sea, polystyrene emerges as the most frequently encountered material (Zhou *et al.,* 2011). One way that MD enters marine waters is through fishing operations (Donohue, 2005; Sinopoli *et al.,* 2020; Unger and Harrison, 2016). According to the results of research by Pauly and Zeller (2016), around 13% of global marine fishing comes from the IO region, this makes it a major contributor to the plastic waste in IO. One of the main causes of plastic trash at sea is fishing industry-related abandoned, lost, and discarded fishing gear (ALDFG) (Lebreton *et al.,* 2022; Richardson *et al.,* 2021), washes up on the coast (Behera *et al.,* 2021; Cordova *et al.,* 2022a; Thiel *et al.,* 2021; Unger and Harrison, 2016), and impacts marine biota (Jacobsen *et al.,* 2010). ALDFG is a significant contributor to MD in the sea and harms the ecology and socio-economics of coastal and near-shore areas (Gilman *et al.,* 2021; Macfadyen *et al.,* 2009). Gilman *et al.* (2022) worked to create the most suitable and promising ALDFG mitigation strategies and priorities in order to enhance fisheries management to reduce the component of global MD originating from ALDFG. Moreover, pieces of plastic rope and small nets constitute debris originating from larger marine plastic debris (MPD) that has harmed the environment. Sunlight mechanically degrades these plastic products into smaller fragments

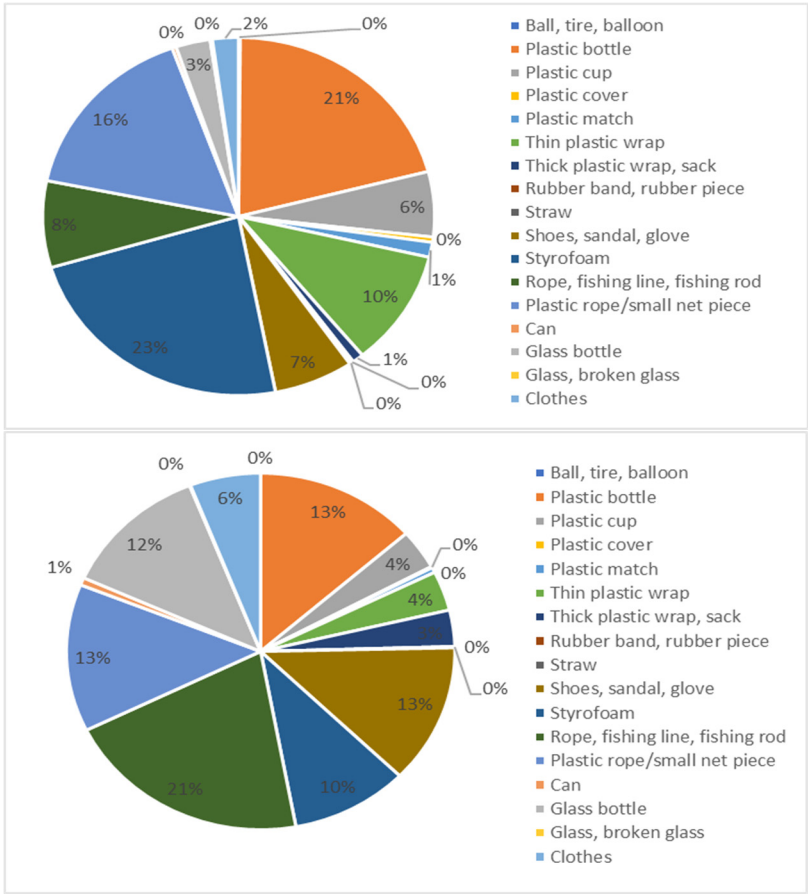

Fig. 3: Percentage of total abundance (top) and weight (bottom) of stranded MD during cleaning at Enggano Island

(Mrosovsky *et al.,* 2009). According to Costa *et al.* (2010), The breakdown of bigger plastics is the main source of fragments (96.7%), and many of these are discovered washed up on the coast (Ivar do Sul and Costa, 2007). A significant portion of the plastic waste located on Enggano Island's coastline has been reduced to small fragments, which complicates the identification of their initial use (Thiel *et al.,* 2021). Overall, the percentage of MD abundance in some of the sub-categories was lower than the weight percentage, possibly because of several sub-categories. However, the number is smaller and has a higher weight, such as rope/fishing line/fishing rod, clothes, and shoes/sandals/gloves (Fig. 3).

Seasonal density of stranded MD

Seasonal factors played a significant role in determining the weight and abundance observed during the survey. Throughout the 12-month sampling period, 16,382 items were gathered from 10 different stations, accumulating to a total weight of 24,826 grams. The average MD abundance during the study was 0.387 ± 0.006 item/m^2, and the average weight was 11.545 ± 0.146 g/m^2. MD abundance during the JJA season ranged from 0.060–0.188 item/m^2, with an average of 0.106 ± 0.008 item/m^2. The SON season were ranging from 0.053–0.248 item/m^2, with an average of 0.107 ± 0.008 item/m^2. The DJF season ranges from 0.027–0.185 item/m^2, with an average of 0.082 ± 0.006 item/m^2. The MAM ranges from 0.029–0.183 item/m^2 with an average of 0.084 ± 0.007 item/m^2 (Fig. 4). Meanwhile, the MD weight during the JJA season ranges from 0.586–14.629 g/m^2 with an average of 4.167 ± 0.326 g/m^2. The SON ranges from 1.193–7.878 g/m^2, with an average of 3.038 ± 0.265 g/m^2. The DJF ranges from 0.711–3.294 g/m^2, with

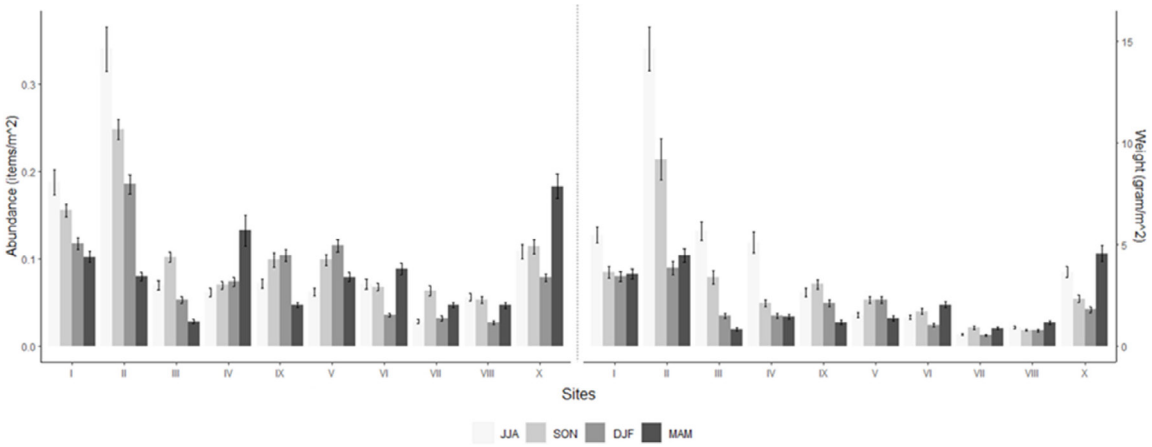

Fig. 4: Marine debris based on abundance (left) and weight (right) in 4 different seasons

an average of 2.013 ± 0.144 g/m^2. The MAM ranges from 0.711–5.205 g/m^2, with an average of 2.290 ± 0.172 g/m^2 (Fig. 4). Analysis using non-parametric statistical tests, specifically the Kruskal-Wallis test, demonstrated that there were significant differences in MD abundances and weights among the various sampling locations.

The JJA data indicates that stations 2 and 1 exhibit the highest levels of MD, recorded at 0.291 item/m2 and 0.161 item/m2, respectively. This pattern is thought to arise from the irregular currents during the southeast monsoon, which differ spatially between the Sumatra coast and Enggano Island, primarily moving in a westward direction. In the DJF, the highest ones are stations 2, 1, 4, and 9 (0.185 item/m^2, 0.118 item/m^2, 0.115 item/m^2, and 0.104 item/m^2, respectively), where the current tends to move from northwest to southeast, with the low current speed at the north area of Enggano Island along the coast of Sumatra. In MAM, the highest abundance was at stations 10 and 4 (0.183 item/m^2 and 0.132 item/m^2, respectively), which tended to have stronger currents than the other seasons from the northwest to the southeast, similar to the pattern of the western monsoon currents. In transition season 2 (SON), the current pattern is almost the same as the southeast monsoon, where the highest abundance is at stations 2, 1, 10, 9, and 4 (0.213 items/m^2, 0.133 items/m^2, 0.130 items/m^2, 0.127 items /m^2, 0.127 items/m^2, respectively). Conversely, stations 5, 6, 7, and 8 show little variation and tend to have lower measurements than other stations, presumably because they are situated on the island's side with a weaker current. Surface currents are anticipated to fluctuate in accordance with the prevailing monsoon patterns (Sprintall *et al.,* 2009). The variations in weight across seasons at each station correspond with the abundance levels. Generally, the seasonal current dynamics in the waters off Enggano Island are consistent with the wind direction patterns (Fig. 5), and surface currents are influenced by wind speed and direction (Wyrtki, 1961).

Findings from the study reveal that a considerable proportion of the debris that accumulates on beaches is plastic, and the minimal presence of non-floating materials like glass or metal is generally seen as an indication that the debris comes from marine sources (Honorato-Zimmer *et al*., 2019). Research conducted by Krishnakumar et al. (2020) in the Andaman and Nicobar Islands and by Lavers *et al*. (2019) in the Cocos (Keeling) Islands analyzed debris that has been washed ashore by ocean. Various studies have proven that currents transport MPD to the islands (Lavers *et al.,* 2019; Pattiaratchi *et al.,* 2022; Suteja *et al.,* 2021; Thiel *et al.,* 2021; Van Der Mheen *et al.,* 2020). According to the results of research by Blickley *et al.* (2016), the trade northeast wind plays an important role in the disposition of debris on the coast of Maui rather than in proximity to urban areas. Moreover, according to Ourmieres et al. (2018), the interplay of coastal currents and onshore winds in the northern Mediterranean Sea affected the gathering and distribution of floating marine debris, leading to its deposition along the coastline

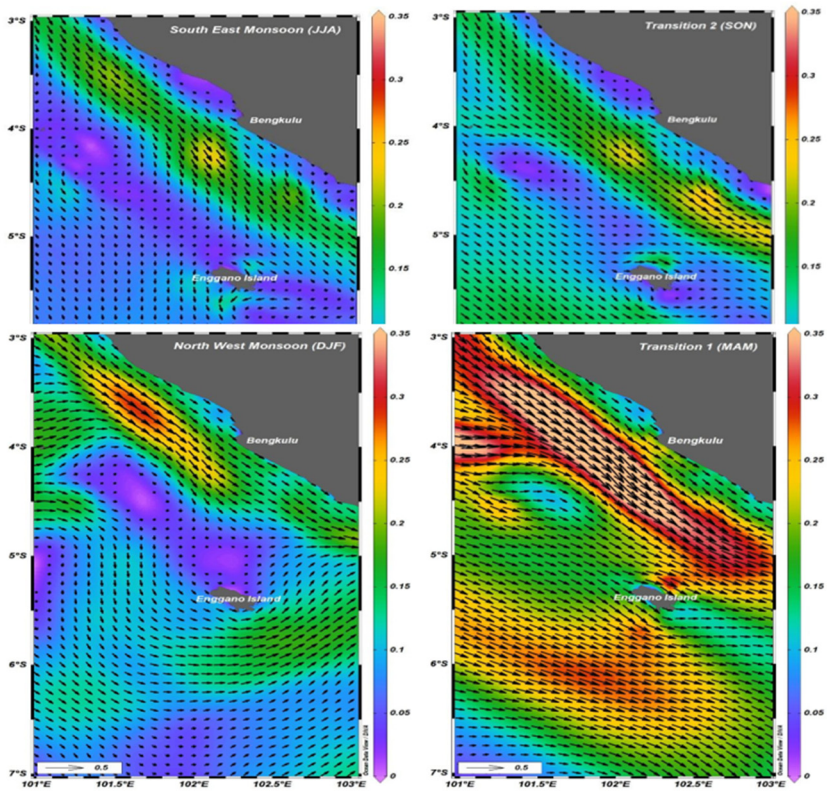

Fig. 5: Seasonal current patterns on Enggano Island

of Antibes in France. Changes in wind direction due to monsoon wind reversal, fronts, and upwelling, for example, are particularly important for IO, oceanography, and topographic features that control the distribution of plastic. The plastic that washes up on the island's coast in IO comes from the sea; the detection using optical remote sensing proves that the concentration of MPD on the beach is a result of deposition from marine sources (Guffogg *et al.,* 2021). Projections indicate that a significant portion of the floating plastic is likely to end up on the shores of the northern Indian Ocean, as the presence of land inhibits the development of a subtropical gyre in that area (Pattiaratchi *et al.,* 2022). Debris dynamics in subtropical gyres and buildup on oceanic islands can potentially be impacted by seasonal or interannual changes in large-scale oceanography (Blickley *et al.,* 2016; Morishige *et al.,* 2007). Analysis using non-parametric statistical methods revealed significant differences in both the abundance and weight of stranded MDs on Enggano Island between seasons. This result is in line with that reported by Cordova *et al.* (2022a), where the abundance and weight of MD differed significantly between the rainy and dry seasons over 12 months of sampling at 18 beaches in Indonesia. Likewise, the results of research by Suteja *et al.* (2021) in Bali vary significantly between seasons. Ryan and Perold (2021) found that the load of trash on the beach peaked during rain events and decreased after rain events in Cape Town, South Africa. Unlike the situation on the Maui shore, where debris accumulation remains consistent throughout the year, these outcomes present a different trend (Blickley *et al.,* 2016). Cheung *et al.* (2016) reported that there is no difference in abundance and weight between seasons; The Pearl River Estuary, situated in the western part of the city, plays a crucial role in shaping the quantity and distribution of plastic waste in Hong Kong.

Seasonal category of MD

In every season across all sampling stations,

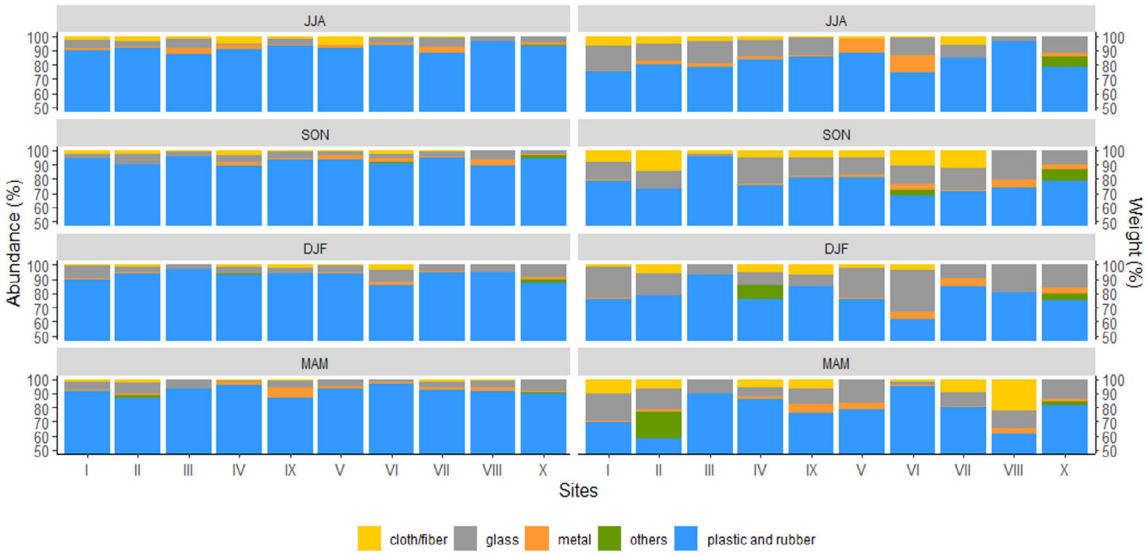

Fig. 6: Percentage marine debris category based on abundance (left panels) and weight (right panels) in 4 different seasons

plastic made up the highest percentage in terms of both abundance and weight. The percentage of the abundance of plastic, metal, glass, clothing, and others in JJA is 91.55%, 1.93%, 4.06%, 2.47%, and 0%. The SON is 92.54%, 1.71%, 4.08%, 1.52%, and 0.15%. The DJF is 92.21%, 0.86%, 5.67%, 1.18%, and 0.06%. The MAM is 91.80%, 2.11%, 4.96%, 1.00%, and 0.12%. Each category's percentage value differs in weight, indicating that even a limited abundance can possess a higher level of importance. The weight percentage of plastic, metal, glass, clothing, and others in JJA is 80.82%, 3.64%, 11.53%, 4.02%, and 0%. The SON is 77.69%, 1.73%, 12.96%, 7.18%, and 0.44%. The DJF is 78.46%, 1.60%, 15.89%, 3.07%, and 0.98%. The MAM was 77.55%, 2.31%, 11.78%, 6.47%, and 1.89% (Fig. 6). The analysis of stranded marine debris revealed that the plastic category comprised five sub-categories with the greatest abundance percentages in JJA. These were pipes, hoses, and pieces, which accounted for 21.27%; Styrofoams at 18.31%; plastic bottles at 14.01%; thin plastic wraps at 12.90%; and plastic cups at 9.64%. In the SON period, the composition of materials is as follows: pipes, hoses, and pieces account for 20.39%; Styrofoams make up 14.58%; plastic bottles represent 14.29%; plastic cups are at 12.89%; and thin plastic wraps are at 9.35%. In contrast, during DJF, the percentages change to 24.24% for pipes, hoses, and pieces; 19.12% for plastic bottles; 14.41% for Styrofoams; 11.46% for plastic cups; and 5.45% for thin plastic wraps. In MAM, plastic bottles dominate at 27.70%, followed by Styrofoams at 17.95%; plastic cups at 13.38%; pipes, hoses, and pieces at 12.00%; and thin plastic wraps at 5.81%. In terms of weight percentage, the plastic category contributing most to the glass bottle sub-category at JJA included Styrofoams at 13.77%, followed closely by plastic bottles at 13.66%, and pipes, hoses, and pieces at 13.56%. Other notable contributions came from shoes, sandals, and gloves at 9.92%, plastic cups at 8.74%, thin plastic wrap at 8.13%, and the glass bottle sub-category itself at 8.74%. In SON, the leading contributors were Styrofoams at 16.12%, plastic bottles at 15.02%, and pipes, hoses, and pieces at 10.86%. Additional contributions included plastic cups at 8.56%, thin plastic wraps at 7.30%, and the glass bottle sub-category at 9.50%. During DJF, the plastic sub-category saw plastic bottles at 19.28%, shoes, sandals, and gloves at 12.18%, and Styrofoams at 12.02%. Other contributions included pipes, hoses, and pieces at 10.17%, ropes, fishing lines, and fishing rods at 7.89%, and the glass bottle sub-category at 12.95%. In MAM, the plastic sub-category was led by plastic bottles at 21.15%, followed by shoes, sandals, and gloves at 14.20%, and Styrofoams at 12.42%. Additional contributions were from plastic cups at 7.11% and the glass bottle sub-category at 10.12%.

Statistically, the MD category stranded on the south coast of Enggano Island exhibited significant differences between the median samples.

The findings of this study reveal that plastic debris constitutes the majority of the waste observed, with its prevalence matching or possibly surpassing the findings from other investigations conducted on coastal areas and the small islands of IO (Table 2). This fact is not surprising, considering that plastic is the most common product used by humans, and debris is increasing exponentially in the world's oceans, including in IO (Borrelle *et al.,* 2020; Pattiaratchi *et al.,* 2022) estimate that 19–23 MMT, or 11%, of plastic debris generated globally in 2016 entered aquatic ecosystems. The results of calculations reinforce this statement by Jambeck *et al.* (2015): In 2010, 192 coastal countries produced 275 MMT of plastic trash, of which 4.8 to 12.7 MMT ended up in the oceans.

Table 2: Comparison of stranded MD with other previous studies in IO

Observation sites	Country	Sampling periods	Number of items	Major debris	Sources
Small island/remote island					
The Chagos Archipelago	Inggris territory	Diego Garcia Atoll: October–November 2021 Egmont Atoll: June–July 2022	136.3 bottles per 100 m transect	-	Savage *et al.,* 2024
St Brandon's Islands	Republik Mauritius	16 – 19 October 2017	25,992 items, over a total distance of 7.2 km	Plastic and plasticised paper (> 50%)	Evans *et al.,* 2011
little and Great Nicobar Islands	India	February to March 2016			
Nallathanni Island	India	16 – 19 October 2017	-	Plastic (86.5%)	Krishnakuma *et al.,* 2018
Andaman and Nicobar Island	India	-	Andaman: Macro – 358 Particles; Meso – 135; Micro – 125 Particles Nircobar: Macro – 925; Meso – 265; Micro – 88 Particles	-	Krishnakuma *et al.,* 2018
Cocos (Keeling) Island	Australia	2017	23,227 items	Plastic (95.41%)	Lavers *et al.,* 2019
Beaches					
Gulf of Mannar	India	February 2018 and March 2019	-	Fishing nets 43.17 ± 5.48%	Patterson Edward *et al.,* 2020
Ampasindava beaches	Madagascar	10 – 23 April 2015	0.158 item/m^2	Plastic (62.34%)5	Gjerdseth, 2017
Alphonse Island	Republic Seychelles	21 June to 2 August 2013	4.743 items/m^2	Plastic (96%)	Duhec *et al.,* 2015
Sri Lanka beaches	Sri Lanka	2016	4.1–158 item/m^2	Plastic (93.3 %)	Jang *et al.,* 2018
Indian north east beaches	India	2018	0.98 ± 0.34 item/m^2	Plastic (84.6 %)	Mugilarasan *et al.,* 2021
Karnataka Beaches	India	October -December 2005	-	Food-based plastics (43%)	Sridhar and Bhat, 2009
Mumbai beaches	India	May 2011 to March 2012	68.83 items/m^2	Fractionation of plastics (41.85%)	Jayasiri *et al.,* 2013
Padang and Aceh	Indonesia	February 2018 to December 2019	Padang: 9.31 ± 0.46 items/m2 Aceh: 5.3 items/m2	Macroplastics (46.3%)	Cordova *et al.,* 2022b
Kualo beaches Bengkulu	Indonesia	August 2019 to January 2020	0.28 – 0.9 items/m2	Plastic (86.66%)	Johan *et al.,* 2020
Enggano Island	Indonesia	June 2021 – May 2022	0.387 ± 0.006 item/m^2	Plastic (91.55% - 92.54%)	The current study

Approximately 9% of the 6,300 MMT of plastic waste produced in 2015 was recycled, 12% was burned, and 79% ended up in landfills or the environment. Should the existing patterns of garbage generation and management remain unchanged, it is estimated that by the year 2050, approximately 12,000 million metric tons of plastic waste will be found in landfills or dispersed throughout the environment (Geyer *et al.,* 2017). In general, the most prevalent kinds of plastic discovered over the 12-month sampling period were the same as when cleaning the beach prior to the monthly sampling: plastic bottles, thin plastic wrap, plastic rope/small net pieces, Styrofoam, and rope/fishing line/fishing rod. As noted by Geyer *et al*. (2017), single-use plastic packaging represents the predominant market for plastics. The majority of this packaging is utilized in the same year it is manufactured, leading to a much higher level of waste generation in the environment from plastic packaging than from construction-related plastics. If this accumulation of MD continues, it will threaten the sustainability and diversity of biodiversity and ecosystems (Kumar *et al.,* 2021). Even though Enggano is one of Indonesia's leading islands, the sustainability of coastal ecosystems is crucial.

Implications and opportunities for work in the future

The findings of this study reveal that plastic constitutes the majority of marine debris on Enggano Island. During the first phase of cleanup, plastic bottles from multiple nations outside of Indonesia were discovered. The entry of MD into the remote island and its accumulation over the years is due to the absence of any previous beach cleaning activities. Several types of unidentified bottles were located, potentially as a result of being discarded long ago or having spent a significant amount of time adrift. Various studies have proven that local and regional currents play a significant role in the dispersion of marine debris in the ocean, leading to its stranding on coastlines and small islands far from the mainland. The entry of MD into the Indian Ocean is closely related to the Indonesian Throughflow, monsoon winds, and current system (Sprintall *et al.,* 2009; Evans *et al.,* 2011; Lavers *et al.,* 2019; Krishnakumar *et al.,* 2020; Van Der Mheen *et al.,* 2020; Purba *et al.,* 2021; Rahmania *et al.,* 2021; Rizal *et al.,* 2021; Alamsyah *et al.,* 2022; Pattiaratchi *et al.,* 2022). Despite the existing limitations in knowledge and funding available to researchers, further investigation into the impact of currents on the distribution and deposition of microplastics has not been pursued. Collaboration is needed for further research to understand the impact of hydrodynamics. Various modeling can be used to estimate this, such as using GNOME, MDC, HAMSOM (Akbar *et al.,* 2022; Rizal *et al.,* 2021; Kisnarti *et al.,* 2021). Pollution by MD has a detrimental impact on ecosystems. Enggano Island, besides having various ecosystems with high biodiversity, is also a habitat and nesting site for turtles. Various studies have proven that MD have a negative impact on ecosystems (UNEP, 2005) and turtles (Domènech *et al.*, 2019; Matiddi *et al.*, 2019), including hindering hatchlings from returning to the sea (Aguilera *et al.* 2018). In addition, fragments of plastic debris were located, presumably fragmented, but because their size was under 2.5 cm, they were neither identified nor recorded. MD can fragment after undergoing physical processes (Andrady, 2015), becoming microplastics and entering the food chain due to ingestion by various organisms (Macali *et al.,* 2018), and can have adverse effects on organisms (Prokić *et al.,* 2019; Petersen and Hubbart, 2021). Addressing the harmful consequences of marine debris pollution requires the implementation of several preventive actions. On Enggano Island, waste management is conducted independently by residents, who typically resort to burying or burning their waste. However, it can still leak to the beach, so the understanding of the importance of waste management must continue to be improved. While various government measures have been implemented to address MD pollution in the environment, these efforts have not proven effective in significantly lowering MD concentrations. Routine cleaning might be a short-term solution in reducing MD, but it is not a solution. In addition to raising public awareness, it is important for the region, together with various countries bordering the Indian Ocean, to jointly commit to the management of marine debris.

CONCLUSION

Enggano is a small, remote island in the tropical region, specifically in the Indian Ocean, where marine debris deposited on the shores poses a serious problem for the existing ecosystem. The results of the research on marine debris that washed ashore on Enggano Island from June 2021 to May 2022 showed

significant spatiotemporal variations. Each season was influenced by differences in marine debris accumulation across stations, as well as the direction and velocity of the seasonal currents. Plastic was the highest percentage found in all locations and seasons, specifically from 91.55 to 92.54%. The most common types of debris in all categories of macrodebris were Styrofoam, plastic bottles, plastic ropes and small net pieces, thin plastic wraps, and plastic cups. The prevailing assumption is that the marine debris that has accumulated on Enggano Island mainly comes from the sea. In addition to examining debris from larger neighboring islands, such as Sumatra, several bottles were analyzed for their branding, language, and provenance from other countries. These countries were China, Switzerland, Sri Lanka, India, the Maldives, Myanmar, Malaysia, Singapore, Thailand, the Philippines, Australia, Seychelles, and the Middle East, with an average percentage of Indonesian brand bottles, foreign brand bottles, and unrecognized brand bottles 58.12%, 19.59%, and 22.29%, respectively. These unidentified plastic bottles, thought to originate from abroad, are characterized by their unusual shape and color, which are not standard in Indonesian production. The survey indicated that both their prevalence and weight differ according to the season. The total marine debris collected at 10 stations over 12 months of sampling in this study was 16,382 items with a cumulative weight was 24,826 g. The average MD abundance during the study and the average weight were 0.387 ± 0.006 items/m and 211.545 ± 0.146 g/m2, respectively. The MD abundance during the JJA season ranged from 0.060-0.188 items/m2, the SON season from 0.053-0.248 items/m2, the DJF season from 0.027-0.185 items/m2, and the MAM season from 0.029–0.183 items/m2. Meanwhile, the MD weight during the JJA season ranged from 0.586-14.629 g/m2, the SON season from 1.193-7.878 g/m2, the DJF season from 0.711-3.294 g/m2, and the MAM season from 0.711-5.205 g/m2. The Kruskal-Wallis non-parametric statistical test results showed that there are substantial differences in MD abundance and weight between sampling locations. These items of marine debris are shaped by and associated with the hydrodynamic dynamics present in oceans across the globe. Consequently, additional studies are required to clarify the critical influence of ocean hydrodynamics and to identify the origins of marine debris that comes from areas outside Enggano Island. Until now, there has been no integrated waste management in Enggano. The results of this study can be the initial basis for the government to create policies to reduce stranded plastic debris for sustainable coastal area management.

AUTHOR CONTRIBUTIONS

D. Purnama performed the conception and design, conducted field sampling, analyzed and interpreted the data, and drafted the original manuscript, and manuscript edition. N.P. Zamani performed the conception and design, critical revision of the manuscript, and supervision. D.G. Bengen performed a critical revision of the manuscript and supervision. R. Saville performed the critical revision of the manuscript, and supervision. M.R. Cordova performed the conception and design, critical revision of the manuscript, and supervision.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
ω	The transect width
ALDFG	Abandoned, lost, and discarded fishing gear
CMS	Copernicus marine service
D	Density
DJF	The northwest monsoon in December–February
Fig.	Figure
g/m²	Gram per square meters
GNOME	General NOAA Operational Modeling Environment
GPS	Global positioning system
ha	Hectares
HAMSOM	The Hamburg Shelf Ocean Model
IO	Indian ocean
JJA	The southeast monsoon in June–August
kg	Kilograms
km	Kilometers
LMI	Low middle income
m	Meters
m²	Meter square
MAM	The first transition or inter-monsoon in March–May
MD	Marine debris
MDC	Mobidrift Client Portal
ml	Mililiters
MMT	Million metric tons
MPD	Marine plastic debris
n	Number
NAP	National Action Plan
netCDF	Network common data form
NOAA	National Oceanic and Atmospheric Administration
ODV	Ocean data view
PAST	PAleontological STatistics
PET	Polyethylene terephthalate
SEM	The south monsoon current
SJC	South Java current
SON	The second transition or inter-monsoon in September–November
UAE	United Arab Emirates

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