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Marine litter pollution on coral reefs of Darvel Bay (East Sabah, Malaysia)

Nadiezhda Santodomingo [a,*], Chris Perry [b], Zarinah Waheed [c], Muhammad Ali bin Syed Hussein [c], Allia Rosedy [c], Kenneth G. Johnson [a]

[a] Department of Earth Sciences, Natural History Museum, Cromwell Road, SW7 5BD London, United Kingdom
[b] Geography, College of Life & Environmental Sciences, University of Exeter, Rennes Drive, EX4 4RJ Exeter, United Kingdom
[c] Borneo Marine Research Institute, University Malaysia Sabah, Kota Kinabalu, Malaysia

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ABSTRACT

Marine litter is recognized as an increasing component of marine ecosystem pollution. In this baseline study, we document the magnitude, types, sources, and potential impacts of litter on six coral reefs in East Sabah. We applied a simplified classification of litter to extract abundance data from video transects. The average density was 10.7 items per 100 m^2. Plastics represent 91% and the remaining 9% were metal, glass, and wood. Most (~70%) plastics are single-use items derived from dumping. Discarded fishing gear accounts for ~25%. Litter pollution increases closer to urban developments, with Sakar reef having higher densities (51 items per 100 m^2), and higher Clean Coast Index (CCI = 10.2, dirty) and higher Plastic Abundance Index (PAI = 4.68) scores. This method could and should be readily integrated into ongoing monitoring programs to support assessments of the extent and magnitude of marine litter pollution on reefs worldwide.

Coral reefs provide essential ecosystem services (i.e. tourism, coastal protection, food and natural products) to millions of people, but are under threat due to multiple human impacts acting at local to global scales (Hughes et al., 2017). Local impacts caused by overfishing, destructive fishing practices, changes in water quality, invasive species, and outbreaks of novel diseases are well documented examples of such disturbances, and have been widely discussed as factors that will collectively reduce the ability of reefs to cope with the global scale effects of increasing atmospheric CO_2 and consequent rises in sea water temperatures (Anthony et al., 2020; Hoegh-Guldberg et al., 2017).

Studies of the impact of pollution on reef ecosystems have included assessments of nutrient enrichment, sewage discharge, pesticides, oil spills and heavy metals (Dubinsky and Stambler, 1996; Fabricius, 2005; Guzmán and Jiménez, 1992; Nordborg et al., 2020; Shaw et al., 2010; Silbiger et al., 2018; Wear and Thurber, 2015). Of increasing concern, however, are the impacts of marine litter, of which plastics are a primary component. The need to understand the scale of plastic pollution and its effects on shallow coral reefs has been recently highlighted in a special publication for the United Nations Environmental Programme (Sweet et al., 2019). It has been estimated that over 300 million tons of plastic are produced every year for use in a wide variety of applications, of which at least 4.8 to 12.7 million tons ends up in our oceans. Plastics comprises up to 80% of all marine litter from surface waters to deep-sea sediments (Jambeck et al., 2015). Despite societal efforts to reduce single-use plastics in the last few years, the COVID-19 pandemic has caused a step backwards in plastic management and indeed aggravated this issue by exponentially increasing the excessive use and consumption of single-use plastics, including personal protective equipment such as masks and gloves (Silva et al., 2021). Plastics will thus represent a long-term issue for the marine environment. In fact, it has been projected that plastic pollution in the oceans will triple by 2040 under a business-as-usual scenario (Lau et al., 2020).

The immediate impacts of macroplastics and other marine litter on reef corals and associated biota are both direct and indirect. Direct impacts include physical damage, substrate covering and entanglement, and gut blockage if items are ingested (Sweet et al., 2019). Litter can also act as an artificial substrate for the colonization of corals (Hoeksema and Hermanto, 2018), and when litter is transported over long distances it can facilitate the spread of invasive coral species (Mantelatto et al., 2020). In addition, large pieces of litter clearly damage the aesthetic value of coral reefs. Indirect impacts of plastics, in particular, include the introduction of pathogenic agents 'hitch-hiking' on the surface and increasing the appearance of diseases in corals (Lamb et al., 2018). In the long term, macroplastics decompose into micro- and nanoplastics that can be unintentionally ingested by corals. They may also become vectors of bacteria and chemicals that are toxic to corals (Allen et al., 2017), and

* Corresponding author.
E-mail address: n.santodomingo@nhm.ac.uk (N. Santodomingo).

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may enter and contaminate the marine food webs (Setälä et al., 2018) on which many people depend (Hicks et al., 2019). These adverse indirect effects are not exclusive to plastics, but most can be extended to a diverse variety of marine litter that also break into micro- and nano-particles that end up accumulating in reef ecosystems.

Following the seminal study of Lamb et al. (2018) on the impact of plastic litter, there has been an increasing interest in quantifying densities of marine litter on coral reefs (e.g. Mulochau et al., 2020 in Mayotte; Putra et al., 2021 in Java), and the collection of data to assess the damage caused by different types of plastic on coral colonies (Mueller and Schupp, 2020). However, most of the focus has been placed on evaluating microplastics within sediments of coral reefs (Cordova et al., 2018; Ding et al., 2019; Huang et al., 2021; Saliu et al., 2018; Tan et al., 2020) and an increasing number of experiments have demonstrated the stress induced on coral polyps by contact with, or ingestion of, microplastics (Allen et al., 2017; Hall et al., 2015; Martin et al., 2019; Tang et al., 2018). However, despite the fact that evaluating the distribution of marine litter is an obvious aspect to be considered in the ecology of coral reefs, this issue has been relatively understudied to date and systematic surveys of litter presence and impacts are still missing from the routine assessments used in the principal monitoring programs worldwide (e.g. Reef Check, AGRRA, CARICOMP, and GCRMN). Project AWARE is a citizen science initiative with a program “Dive Against Debris”, in which voluntary divers collect litter from the seafloor, but from their datasets it is not possible to identify which specifically correspond to coral reefs (Roman et al., 2020). In addition, the most recent list of healthy coral reef indicators (available at https://www.icriforum.org/supporting-materials/) does not explicitly include any reference to marine litter or plastic pollution (Corcoran et al., 2020). With shallow coral reefs declining at unprecedented rates worldwide (GCRMN, 2021) and litter pollution escalating exponentially (UNEP, 2019), it has become a priority to evaluate the extent and effect of anthropogenic litter on marine ecosystems and how to manage it (Rangel-Buitrago et al., 2020; Williams and Rangel-Buitrago, 2019).

Coral reefs located in coastal areas, and particularly those adjacent to major urban settlements, are potentially more prone to marine litter impacts due to their proximity to the main sources of waste input and dumping (Heery et al., 2018). During survey work to document the distribution of corals in reef habitats of Darvel Bay, East Sabah (Malaysia) we observed that the presence of a variety of plastics and other litter on reefs near Lahad Datu city was evident to such an extent that we considered it imperative to redesign our methods and quantify the densities of marine litter pollutants. The terms marine debris (NOAA, 2021) and marine litter (UNEP, 2021) are synonyms and both are used in the literature (e.g. marine debris: Putra et al., 2021; Roman et al., 2020; Thiel et al., 2013; e.g. marine litter: Abu-Hilal and Al-Najjar, 2009; Mueller and Schupp, 2020; Mulochau et al., 2020). In this study we have adopted the term marine litter as “any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment” (UNEP, 2021). The principal aim here is to establish a baseline of the magnitude, types, sources, and potential impacts of marine litter on coral reefs in Darvel Bay. We propose, for the first time, the integration of two indices into the assessment of marine litter pollution in coral reefs: the Clean Coast Index and the Plastic Abundance Index (Rangel-Buitrago et al., 2021a). Both have previously been used in the evaluation of other coastal ecosystems including beaches and rocky shores. We hope that our outcomes will help highlight the growing and problematic nature of plastic pollution on reefs in this region and will help local managers and authorities to take action to conserve these unique habitats.

Darvel Bay is the largest bay on the east coast of Sabah and is connected to the Pacific Ocean through the Sulu-Celebes Sea. Coral reefs in this bay are mainly fringing reefs developed around numerous islands (Ditlev et al., 1999). This area is located at the north corner of the Coral Triangle region, in a region characterized by high levels of marine biodiversity (Waheed and Hoeksema, 2013). Mangrove ecosystems flourish along the coastline. They are associated with the numerous small freshwater catchments, especially between the mainland and Sakar Island, and around the estuaries of the Silabukan and Tingkayu rivers, located at the northeast and southwest margins of the bay, respectively (Fig. 1).

Climate in this region is seasonally controlled by the Indo-Australian monsoon system, with a dominant northeast monsoon between the months of November to March resulting in a rainy season, and the southwest monsoon between the months of May to September during the dry season (Waheed and Hoeksema, 2013; Walsh, 1996). The tidal pattern is mesotidal, ranging between 2 and 4 m. Simulation models have shown that the water circulation and current pattern of Darvel Bay is mainly controlled by tidal currents (Saleh et al., 2007). The strong tidal current allows open sea water to enter at the northern part of the inlet, where the Silabukan river runoff has a high effect. Water then circulates towards the west with strong currents along the passage between Sakar Island and mainland, to finally move to the south of the bay before returning back to the open sea. This water circulation pattern is also controlled by the uneven bathymetries, small islands and coastal morphology (Saleh et al., 2007).

The distribution of human populations is related to different levels of coastal development and economic activities in this region. Lahad Datu and Kunak are the two most rapidly developing cities in this area, with estimated populations of 27,887 inhabitants and 13,823 inhabitants, respectively, although most of the population are distributed in the proximal rural areas with nearly 200,000 people in Lahad Datu and 61,000 in Kunak (Department of Statistics, 2010). The principal economic activity is oil-palm plantation and processing, and to a lesser extent artisanal fisheries and other agricultural activities such as the production of rubber, cocoa, and copra (dried kernel of coconut) to make cooking oil (Phua et al., 2018). Wildlife touristic activities are offered in the nearby forests of the Danum Valley Conservation Area and the Tabin Wildlife Reserve located 65 km west and 48 km east of Lahad Datu, respectively. The recently created Silam Coast Conservation Area, located between Lahad Datu and Kunak, is expected to promote the geotourism around two coastal geosites (Isnain et al., 2017).

In this work, we analysed the magnitudes, extent, and environmental impacts of litter in six coral reef localities of Darvel Bay, East Sabah, Malaysia (Table 1 and Fig. 1). These reefs are influenced by a range of environmental conditions determined by the proximity to other coastal ecosystems (e.g. mangroves, estuary, and river outlet) and human influence (e.g. urban center, fish farm, and recreational diving), and one is protected in a conservation area (Table 1). Video surveys were performed with a GoPro7 camera using underwater laser pointers as a scale of reference (10 cm). During April 2019, we surveyed five transects (10 $\times$ 2 m) in five reefs at 5 m, 10 m, and 15 m depth, except in Sakar North, where the reef did not extend below 11 m depth. At this locality, data was acquired only for 5 m and 10 m depth. Surveys in the Blue Lagoon were carried out in October 2019, and only three transects were surveyed, so the total area surveyed per depth at this locality was 60 m^2, while in the other localities a total area per depth accounted to 100 m^2.

We counted every litter item that was distinguishable in the video transects, typically those larger than 5 cm. Marine litter was recorded following the typologies, sub-typologies, and buoyancy characteristics by the OSPAR (2010), Rech et al. (2014), and Rangel-Buitrago et al. (2017) classifications, respectively. We have split the main groups from those lists into ten main typologies: plastic (PLT), textiles (TEX), rubber (RBR), paper (PAP), glass (GLA), wood (WOO), metal (MET), ceramics (CER), construction materials (CON), and sanitary waste (SAN). Sub-typologies were also defined for plastic and metal items. Wood items were mostly manmade articles, such as fragments of wooden fences, stilt-houses, or fish enclosures. A code file is available (Table S1) with the list of taxa and benthic categories, including marine litter that can be imported into the software Coral Point Counter (CPCe) (Kohler and Gill, 2006). Data from the five transects per depth were then combined and expressed as density of items per 100 m^2 to facilitate comparisons with

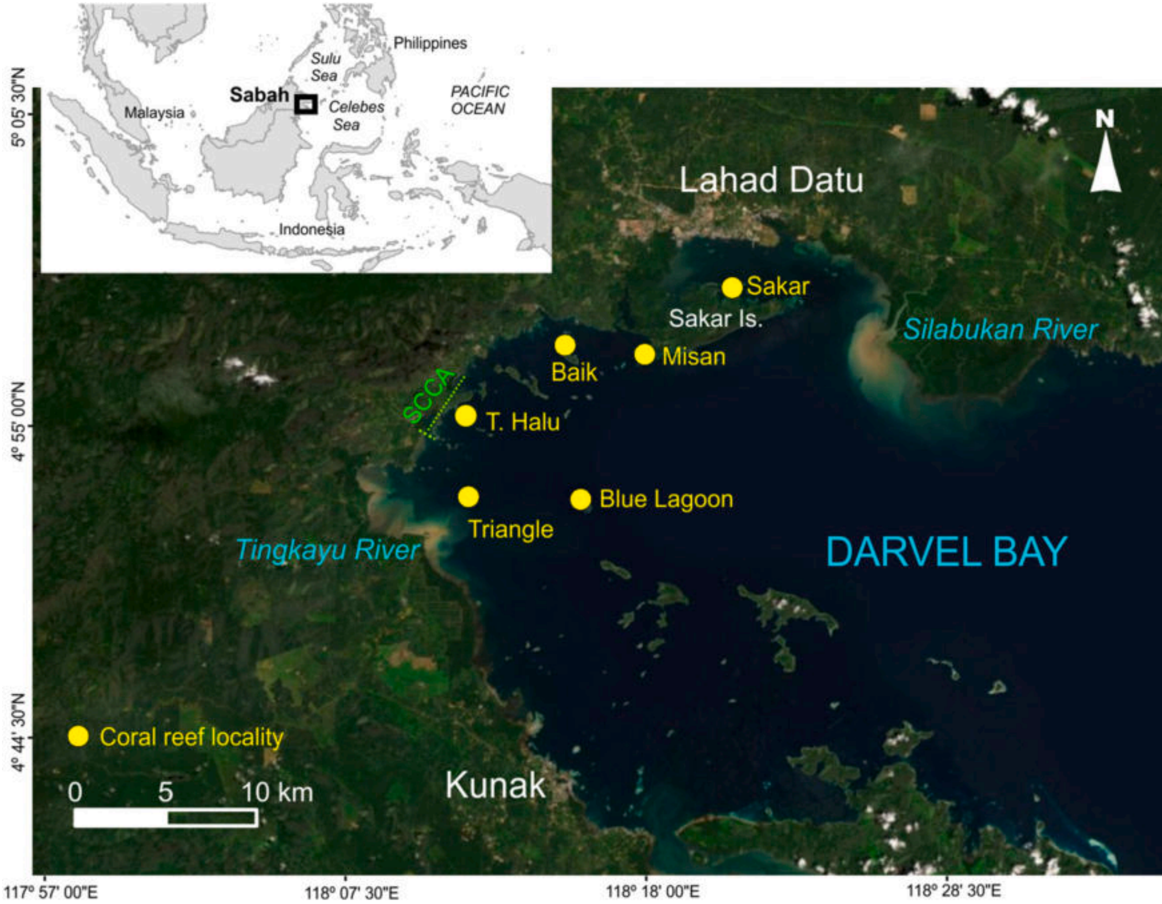

Fig. 1. Location of the studied coral reefs in Darvel Bay (East Sabah, Malaysia), showing the main cities, rivers, and the recently created Silam Coast Conservation Area (SCCA).

Table 1
Coral reef localities surveyed in Darvel Bay (East Sabah, Malaysia).

Code	Locality	Adjacent coastal environment and human activities
Sa	Sakar	Mangroves/urban
Mi	Misan	Mangroves/estuary
Ba	Baik	Fish farm/recreational diving
Th	Tumunong Halu	Mangroves/conservation area
Tr	Triangle	Near Tingkayu river outlet
Bl	Blue Lagoon	Semi-atoll/recreational diving

previously reported data on marine litter in coral reefs. Different types of marine litter were also grouped and used to determine the possible economic sector or human activity from which they originated (source). In this work, categories of marine litter were categorized according to the Ocean Conservancy Classification (Ocean Conservancy, 2010) which relates litter items with the most probable activity or economic sector, responsible for its origin and potential source.

Following the methodological framework developed for monitoring marine litter in coastal areas, we applied two indices to determine the marine litter and plastic influence in the reefs of Darvel Bay. This allows comparisons with other studies of marine and coastal ecosystems. We propose to use the **Clean Coast Index (CCI)** developed by Alkalay et al. (2007) for plastics, and later modified by Rangel-Buitrago et al. (2021a, 2021b) to account for all marine litter in an ecosystem. We applied this index for the first time to coral reefs, in order to estimate the *cleanliness* of a coral reef, i.e. the state of being free of marine litter. The CCI was calculated using the formula:

$$CCI = \frac{\sum litter\ items}{Area} * 20$$

where CCI is the number of litter items seen per square meter (density), multiplied by a constant K = 20 for better interpretation of the data and in order to make the picture clearer for the public (Alkalay et al., 2007). The CCI classifies the marine litter coverage into five categories that range from “clean” to “fully covered by marine litter” (Table S2).

The second index used was the **Plastic Abundance Index (PAI)** developed by Rangel-Buitrago et al. (2021a, 2021b) and previously used on beach ecosystems only. The PAI determines the abundance of plastic relative to the total amount of marine litter items recovered along each sampling unit. The PAI for each one of the reef localities was calculated using the formula:

$$PAI = \frac{\frac{\sum plastic\ litter}{Log\ 10 \sum total\ litter\ items}}{Area} * 20$$

where PAI is the number of plastic items per square meter, considering the existing relationship between plastics and the log-transformed number of all marine litter items observed within the sampled area. The PAI allows the categorization of the coral reef in terms of plastic presence according to five classes that range from “very low abundeance” to “very high abundance” (Table S3).

These indices, both the CCI and the PAI for each coral reef, were integrated into a dynamic table with the CCI type in rows and the PAI type in columns, using the percentile technique (Langford, 2006) in a similar approach of that in Rangel-Buitrago et al. (2021b). This analysis allows the classification of the coral reefs into a conventional three-color traffic light scale (Table S4):

- Green is used for clean to very clean coral reefs with very low amounts of plastic items, where *protection* measures are necessary to keep current conditions.
- Orange represents moderate cleanliness coral reefs with low to moderate amounts of plastic items, where specific *mitigation* measures are necessary for improvement.
- Red describes dirty to extremely dirty coral reefs with a high to a very high number of plastic items, where urgent *intervention* and even *restoration* measures are necessary.

An additional ordination analyses was performed in order to explore differences in litter composition among reef localities, and it is included in the supplementary information.

Live coral cover is relatively high in the sampled reefs of Darvel Bay, with a maximum of 46–51% in Baik and a minimum of 33–39% in Sakar (Santodomingo et al., 2021). Coral growth forms and genera vary among localities. Foliose and platy growth forms of *Leptoseris* spp. (Waheed et al., 2015) are dominant in the highly turbid reefs of Sakar, massive and branching *Porites* are very common in Baik and Misan, while large branching and table acroporids are dominant in the shallow waters of the Blue Lagoon. Triangle reef lies in front of the river and shows a high abundance of leather corals (*Sinularia* and *Lobophytum* spp.), while large colonies of the blue coral *Heliopora* and branching *Porites* were more common in Tumunong Halu (Santodomingo et al., 2021).

Marine litter was found in all six reefs at most depth ranges, except in Triangle Reef at 15 m depth and Blue Lagoon at 5 m depth, where no litter was observed (Tables S5 and S6). A total of 176 items were found in the transects and included four out of the ten main types of marine litter. Plastic items accounted for 91% of all marine litter, while the remaining 9% represented other items such as metal, glass, and wood (Table 2). In addition, textiles (one abandoned t-shirt), construction materials (concrete bricks), and paper (one cardboard box) were also observed out of the surveyed transects.

Densities of marine litter varied among the reef localities with a minimum of 3.0 ± 2.1 (mean ± SE) items per 100 m^2 in Triangle reef and a maximum of 51 ± 3.3 items per 100 m^2 in Sakar (Fig. 2a). In terms of plastic presence, the mean density among localities was 9.6 ± 3.6 items per 100 m^2 (Table 2). Plastics represent the majority of items in all localities, and their relative abundance varied from 75% in Blue Lagoon to 100% in Tumunong Halu (Fig. 2a). The plastics observed belong to eight of the 54 plastic/polysterene categories defined in the OSPAR (2010) classification (Fig. 2b). Four out of the eight plastic types account for the 77% of the total plastic items found, from which the most abundant were other plastic items that represent 24%, followed by fishing nets/lines (21%), plastic bags (19%) and plastic bottles (13%) (Fig. 2b). In terms of plastic types per locality, Sakar has representation of six out of eight plastic types, followed by Baik with five types, Triangle with four and in the remaining three localities only three types of plastic were observed (Fig. 2b). In terms of percentage of plastic types per locality, fishing nets/lines represented 69% in Tumunong Halu, 55% in Misan, and 37% in Blue Lagoon (Fig. 2b). The complete dataset is presented in the Supplementary Material (Table S5) and examples of litter found in the reefs are shown in Fig. 3.

The mean densities of plastic items in Darvel Bay (9.6 ± 3.6 plastic per 100 m^2) fall within the range of 2.0 to 10.9 items per 100 m^2 reported for reefs in Southeast Asia by Lamb et al. (2018), although it is concerning that the maximum density observed in Sakar reef (47.0 ± 4.0 items per 100 m^2) is about twice as high as the maximum found in their study (25.6 items per 100 m^2 in Indonesia). Regarding the total number of marine litter items, densities in Darvel Bay (10.7 ± 3.8 items per 100 m^2) are higher than in remote reefs from Mayote with 0.8 ± 0.3 items per 100 m^2 (Mulochau et al., 2020) and a maximum of 7.8 ± 0.8 items per 100 m^2, and urban reefs in Jakarta with 2.7 items per 100 m^2 and a maximum 6.7 items per 100 m^2 (Putra et al., 2021). However, our data is much lower if compared with touristic areas in the Gulf of Aqaba where densities are as high as 280 items per 100 m^2 (max. 600 items per 100 m^2) (Abu-Hilal and Al-Najjar, 2009).

The estimation of the CCI and PAI index for the six localities in Darvel Bay show that most reefs are classified as "very clean" with "low abundance" of plastics, while Sakar reef is "dirty" and has "high abundance" of plastics (Table 3 and Fig. S1). The mean PAI for the study area is 1.4 ± 0.7, so reefs in Darvel Bay grouped into the "moderate" type, where a considerable quantity of plastics are polluting the reef environment.

The ordination analysis suggests two main groups, one including Sakar reef with the highest densities of marine litter (Group A) versus the other reefs containing less marine litter (Group B) (Fig. S2). These two groups correspond with the traffic-light levels obtained by the sector analysis (Fig. S1).

The 176 marine litter items counted in the surveys were sorted into the main types of sources or anthropogenic activities (Table 4). Three main activities were identified in relation to the marine litter observed

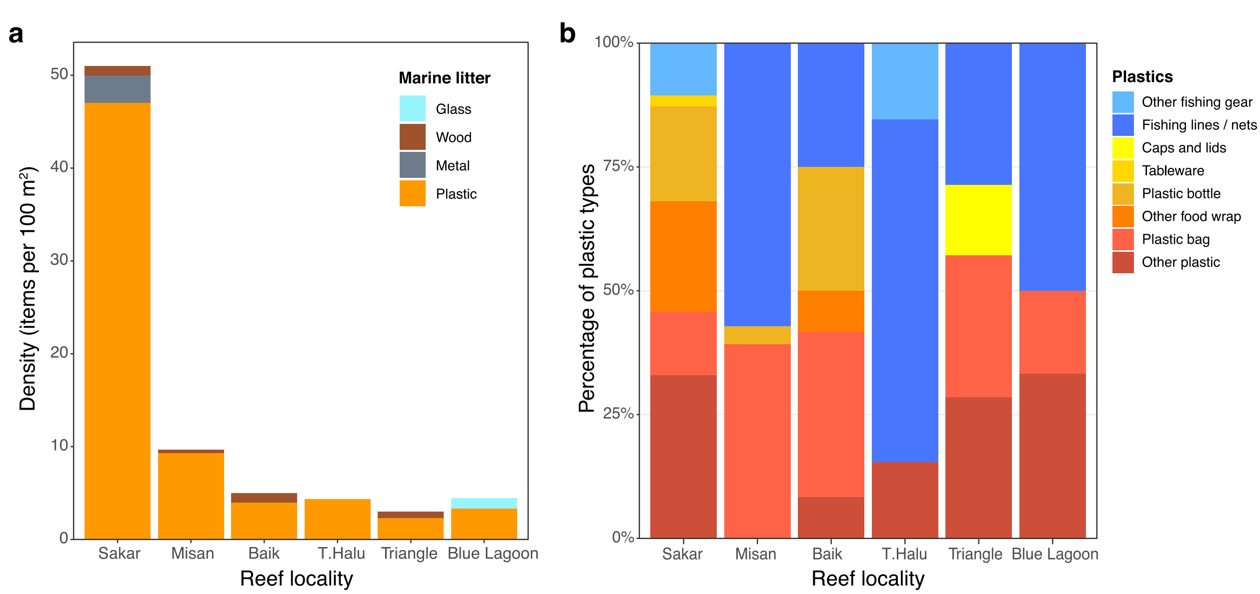

Fig. 2. Density (items per 100 m^2) of marine litter in coral reefs of Darvel Bay (a) and percentages of plastic types in each reef locality (b).

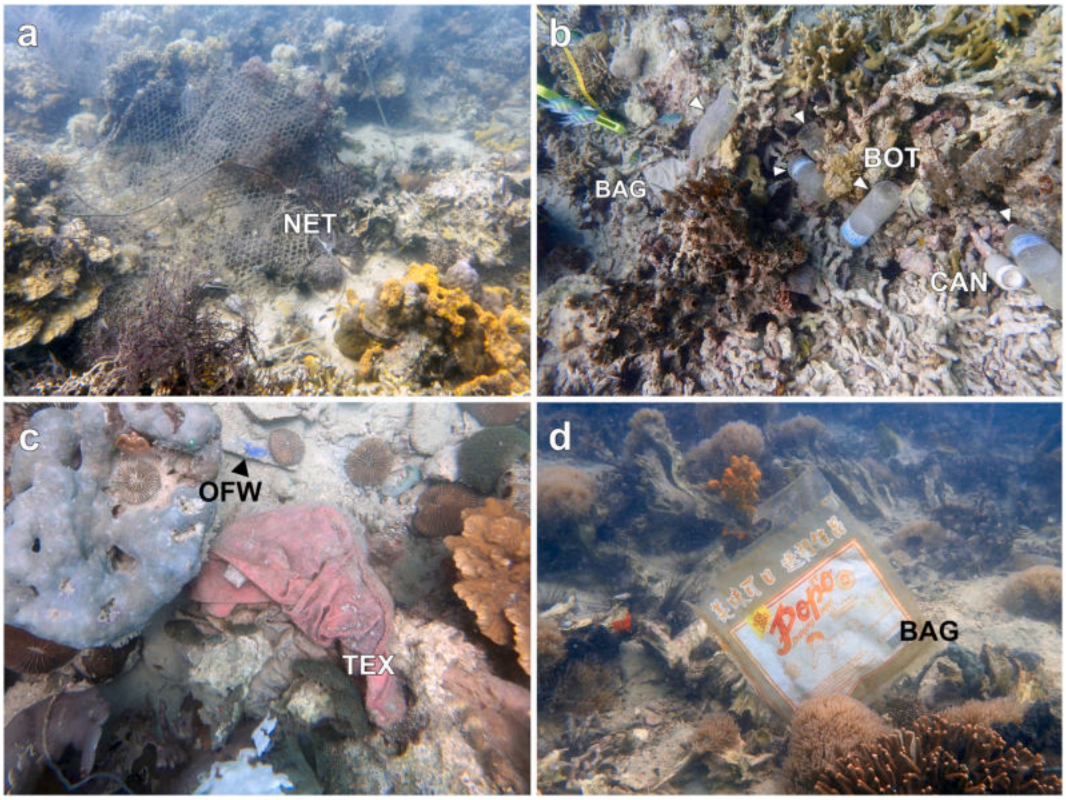

Fig. 3. Examples of marine litter found in Darvel Bay reefs: Abandoned fishing net in Triangle Reef at 10 m depth (a), plastic bags (BAG), plastic bottles (BOT), and aluminum cans (CAN) in Baik at 5 m depth (b), other food wrap (OFW) and textiles (TEX) in Sakar at 5 m depth (c), and plastic bag (BAG) in Sakar at 10 m depth (d). Photo credit: a&b Nadia Santodomingo, b&d Dominic Monteroso.

Table 2
Total densities of marine litter (ML) on reefs of Darvel Bay.

	Plastic	Metal	Glass	Wood	Total
Total	160	6	2	8	176
Percentage	91	3	1	5	100
Mean ML per 100 m^2 ± SE	9.6 ± 3.6	0.4 ± 0.3	0.2 ± 0.2	0.5 ± 0.2	10.7 ± 3.8

on Darvel Bay reefs:

Marine litter related to dumping activities: Six categories of plastic and wood were related to dumping activities, and they represent 69.8% (123 items) of all marine litter found in the study area. Most of the dumped items are plastic bags (17.0%), plastic bottles (12.5%), food wrapping (12.5%), and other plastic items (21.6%) that had been partly disintegrated, fragmented, or covered by fouling biota and could not be identified. Wood pieces used in construction or furniture parts were also seen in most reefs, except in Tumunong Halu and Blue Lagoon. Dumping activities can be associated with inadequate waste management systems on land, so significant proportions enter the sea via rivers. Dumping may also be done directly into the sea, in particular, given the presence of many stilt-house villages along the coast in Darvel Bay. The poor management of waste is a recognized problem, as it has been estimated that up to 85% of the total waste produced in Malaysia is disposed of inappropriately (WWF, 2020).

Marine litter related to ocean and waterway activities: Two plastic categories were directly associated with marine activities, and they represent 25.6% of the items. Both are related to fishing; derelict fishing nets and fish lines (entangled nylon). These account for 18.8% of marine litter, and the remaining 6.8% are other fishing gear, mainly ropes. These items can remain in the reefs for several years, as they are easily entwined into coral colonies, particularly those with branching forms, causing damage and loss of coral tissue, and the eventual death of coral colonies (Hoeksema and Hermanto, 2018; Valderrama Ballesteros et al., 2018).

Marine litter related to shoreline and recreational activities: A smaller proportion of items (4.5%) are commonly associated with shoreline and recreational activities, including drink cans (1.7%), food cans (1.7%) and glass bottles (1.1%). These items are referred to as "non-buoyant", as they do not float and are too heavy to be transported over long distances. The low representation of these items may be related to the low level of marine tourism in Darvel Bay, although some

Table 3
Reef site classification according to the Clean Coast Index - CCI (Alkalay et al., 2007) and Plastic Abundance Index – PAI (Rangel-Buitrago et al., 2021a, 2021b).

Code	% plastic	% other litter	CCI	CCI type	PAI	PAI type	Group (NMDS)	CCI-PAI level
Sa	92.2	7.8	10.2	Dirty	4.68	High abundance	A	Red
Mi	96.6	3.4	1.9	Clean	1.28	Moderate	B	Orange
Ba	80	20	1.0	Very clean	0.68	Low abundance	B	Orange
Th	100	0	0.9	Very clean	0.78	Low abundance	B	Orange
Tr	77.8	22.2	0.6	Very clean	0.49	Low abundance	B	Orange
Bl	75	25	0.9	Very clean	0.74	Low abundance	B	Orange

Table 4
The amount and densities per marine litter categories observed in reefs of Darvel Bay. Potential sources and human activities of marine litter were defined based on OSPAR (2010). Plastic (PLA), Wood (WOO), Glass (GLA), and Metal (MET).

OSPAR code	Type	Subtype name	Subtype code	Source	Amount	Percentage	Densities (items per 100 m^2)
2	PLA	Plastic bag	BAG	Dumping	30	17.0	1.9
4	PLA	Plastic bottle	BOT	Dumping	22	12.5	1.3
46, 48	PLA	Other plastic	OPL	Dumping	38	21.6	2.2
6, 19	PLA	Other food wrap	OFW	Dumping	22	12.5	1.3
21, 22	PLA	Tableware	TW	Dumping	2	1.1	0.1
15	PLA	Caps and lids	CAP	Dumping	1	0.6	0.1
35, 115	PLA	Fishing lines/nets	NET	Ocean/waterway	33	18.8	1.9
31, 32	PLA	Other fishing gear	OFI	Ocean/waterway	12	6.8	0.7
12	WOO	Wood	WOO	dumping	8	4.5	0.5
91	GLA	Glass	GLA	Shoreline and recreational	2	1.1	0.1
78	MET	Aluminum can (drink)	CAN	Shoreline and recreational	3	1.7	0.2
82	MET	Metal (other food can)	TIN	Shoreline and recreational	3	1.7	0.2
Total					176	100	11.1

recreational diving is done in Baik and Blue Lagoon reefs (Table 1), where most of this type of litter was found.

About 60% of global marine plastic enters the ocean from China, Indonesia, Malaysia, the Philippines, Thailand and Vietnam (WWF, 2020). Darvel Bay is located at the crossroads of three of these major polluters in Southeast Asia: Malaysia, the Philippines and Indonesia (WWF, 2020). Malaysia is one of the top plastic consumers in Asia with a rate of 62 kg/capita/year which positions the country in the 28th place in the world's top plastic polluters in 2021 (World Population Review, 2021). About a third of the plastic (16.78 kg/person/year) correspond to single-use plastics and packaging for household goods (Fauziah et al., 2021; WWF, 2020). This amount becomes more concerning, as the average total recyclable material per capita is just 0.12 kg/person/day, so waste management in Malaysia depends greatly on landfills where about 89% of the collected waste should end up (Abd-Manaf et al., 2009; JPSPN, 2015). Since less than 15% of the waste is safely disposed of and most is inapropriately dumped (WWF, 2020), the amount of waste that effectively ends up in the ocean in this region may be of high quantities (Fauziah et al., 2021). However, more work is required to fully document this issue.

As in most countries globally, assessments of marine litter in Malaysia have focused on beach ecosystems. The combined data of marine litter collected during the International Coastal Clean-up Day and World Clean-Up Day 2019 was estimated at 41,884 kg and 868,042 items from surveys along 2415.5 km of the Malaysian coast, with an average of 359.36 items per km (Ocean Conservancy, 2020). The most commonly-collected items from beaches are plastic bottles (23%), cigarette butts (21%), plastic bags (13%) and food wrappers (12%). In total, all plastic accounts for >85% of the marine litter items. In agreement with the global trend, these numbers have been increasing since the Coastal Clean-up program started in 2015.

In this analysis, we applied two indices to qualify the status of "cleanliness" (CCI) and "plastic abundance" (PAI) in the studied coral reef ecosystems. These indices can be used as direct indicators of the aesthetic value of a coastal ecosystem but might also give a first sign of its health status when applied to a coral reef. Previous studies have shown that the prevalence of diseases in coral colonies increase from 4 to 89% on reefs in the presence of plastic litter (Lamb et al., 2018). The evaluation of diseases and loss of coral tissue related to the presence of marine litter was out of the scope of our baseline study. However, one can expect that a more robust dataset will allow modeling the prevalence of diseases as related to the density of marine litter (items/m^2) and the identification of thresholds for when a reef passes from a healthy to a deteriorated state. In this sense, the scale values to classify the reefs with the indices could be adjusted accordingly. The abundance of marine litter can be 100 times higher on beaches than on coral reefs, so the thresholds for cleanliness status might need to be adjusted to properly reflect the health condition of polluted reefs. In order to not give the false impression that reefs are not significantly impacted by relatively low densities of litter when compared with high values found on beaches, we could also explore the use of different scaling factors when estimating the CCI and PAI indices. Additional data on the abundance of marine litter on reef systems and its impact on ecosystem health would allow this modification.

Remarkably, the integration of both indices into the sector analysis (Tables 3, S4) seems to counteract the limitation of applying each index separately and it offers a more suitable approach as the combined interpretation has much lower thresholds. In that sense, our outcomes show that the traffic-light scale would be a better tool to assess the impact of marine litter pollution in coral reefs than the individual indices. This traffic-light scale would also allow effective communication with local managers and stakeholders to take actions to maintain the status of reefs free of litter, to establish mitigation measures to improve the condition of reefs with low to medium impact of marine litter, or even to restore reefs with higher levels of litter pollution.

Our data from Darvel Bay reefs reflect the composition of marine litter seen in beaches, as the majority of items are plastics (91%), mostly plastic bags, plastic bottles, and food wrapping. However, in our surveys we did not observe cigarette butts, one of the top items collected in beaches, because they are either too small (1 to 2 cm) to be seen in our video surveys, or simply because their short-term buoyancy limits their transportation into the reefs. Similarly, we did not observe highly bouyant styrofoam pieces on the reefs in Darvel Bay, despite their extensive use by the local population as take-away food and cool boxes.

These results suggest that higher amounts of marine litter tend to accumulate in beaches than on coastal coral reefs. For example, if compared with densities from beaches protected in marine parks of Peninsula Malaysia (Fauziah et al., 2019) such as Pulau Payar (10 ± 8 items m^2) and Pulau Tioman (19 ± 3 items/m^2), marine litter on reefs could be approximately 1% of abundance the marine litter seen on beaches. However, data from nearby beaches in Sabah are still missing to provide a reliable comparison. In this area, it would also be highly recommended to assess the quantities of marine litter in mangroves as they are the dominant ecosystem along the coastline, particularly around Lahad Datu and Sakar Island.

Marine litter pollution was significantly higher on Sakar reef, followed by Misan and then densities decrease on the reef localities nearer to the center of the bay. This pattern of pollution is clearly controlled by the proximity to the city Lahad Datu and relate to the nature of persistent-buoyant litter items, as their abundance declines with the distance from the main source of pollution (Rech et al., 2014). This pattern also corresponds with the water circulation movement in the bay (Saleh et al., 2007), so most of the dumping materials would remain in the vicinity of the principal urban area, but some could be transported through the narrow channel running between Sakar Island and the mainland towards Misan. Just a small fraction would reach the reefs in the central part of the bay. Regarding the type of plastic and the related anthropogenic activities, most of the plastics observed are single-use items such as plastic bags, bottles, and food wrapping. In comparison to previous studies of coastal ecosystems (Jambeck et al., 2015; Thiel et al., 2013), our data show slightly higher proportions of sea-based versus land-based activities (30% and 70%, respectively), which can be related to the relatively higher fishing pressure on reefs of Misan and Tumunong Halu.

The fact that nearshore and urban reefs are the most impacted by litter pollution is highly concerning because these shallow turbid reefs might be able to cope better with recurrent bleaching events. For example, corals in urban reefs from Singapore have shown progressively more resilience to bleaching events from 1998 to 2010 (Guest et al., 2012, 2016) and nearshore reefs in the Great Barrier Reef showed only focal bleaching during the mass bleaching event that destroyed a third of the corals in the outer barrier during 2016-17 (Morgan et al., 2017). Indeed, our preliminary observations show that during the 2020 bleaching event, only 12–15% coral colonies show some signs of bleaching in turbid reefs of Sakar while 46–53% coral colonies were mostly or completely bleached in the clear-water reefs of the Blue Lagoon (Rosedy et al., 2021). Because of their resilience to increasingly more common and higher-magnitude bleaching events, it has been proposed that turbid shallow reefs might act as refugia habitats giving a glimpse of hope in the face of the current climate crisis (Cacciapaglia and van Woesik, 2015; Sully and van Woesik, 2020). However, their critical role as refugia might be under threat by litter pollution as shown in our study. Although there is no strong evidence that the levels of marine litter currently observed on urban reefs will result in widespread death of corals as seen in mass bleaching events, it is important to maintain the health of these potential refugia by ensuring that litter levels do not increase. This imminent risk adds one more reason to take urgent actions to assess the impact of marine litter on reefs close to the coast and adjacent to urban centres.

Given the negative impacts of marine litter on the health of coral reefs and the challenges ahead, we suggest there is a need to integrate simplified lists of marine litter typologies into standard reef surveys. These could range from citizen-driven initiatives such as Reef Check and Project AWARE to international monitoring programs such as AGRRA, CARICOMP, and the GCRMN. In this way, the community can perform a systematic monitoring and quantification of marine litter that allow comparisons and evaluation of the scale of magnitude of this problem in different regions. Although it is still too early to define the dimensions of the transects, our results combined with data from previous surveys suggest that sampling an area of at least 100 m^2, either by one transect of 100 m × 1 m or split into shorter transects (e.g. five transects of 20 m^2, either 10 m × 2 m or 20 m × 1 m) would be representative enough to get a snapshot of the distribution of marine litter on coral reefs. A sampling unit of 100 m^2 has the advantage of being compatible with the methodology of Reef Check (Hodgson, 2001: 100-m transects), CARICOMP (CARICOMP, 2001: 5 permanent transects of 10 m length), and AGRRA (Lang et al., 2013: transects of 10 m). This would allow assessments of marine litter with relatively little extra effort and low additional cost. Further surveys are needed to define the number of sampling units per locality, as in our study we observe a high variability within each locality. Certainly, the early establishment of standard methodologies for sampling, analyzing, and reporting the data will facilitate comparability of results in the long term.

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CRediT authorship contribution statement

Nadiezhda Santodomingo: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Chris Perry:** Conceptualization, Methodology, Writing – review & editing. **Zarinah Waheed:** Methodology, Writing – review & editing. **Muhammad Ali bin Syed Hussein:** Methodology, Writing – review & editing. **Allia Rosedy:** Methodology, Writing – review & editing. **Kenneth G. Johnson:** Conceptualization, Methodology, Validation, Formal analysis, 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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