Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(4): 2487 – 2512 (2025)
www.ejabf.journals.ekb.eg

Characteristics and Potential Source of Marine Debris in an Indonesian Remote Island: A Case Study of Lemukutan Island

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ARTICLE INFO

Article History:
Received: June 2, 2025
Accepted: Aug. 3, 2025
Online: Aug. 20, 2025

Keywords:
Marine debris,
Plastic pollution,
Numerical modeling,
Lemukutan Island

ABSTRACT

The accumulation of marine debris on Lemukutan Island poses a significant threat to the island's aquatic environment and sustainable tourism. This study investigates the abundance and spatiotemporal characteristics of marine debris along the island's coastline and evaluates the dominant sources contributing to its presence. Sampling was conducted twice, in May and November, representing the first and second monsoon breaks, using methods adapted from the NOAA Marine Debris Program. Results revealed an average abundance of 4.4 ± 0.08 items/m² and an average weight of 22.3 ± 0.46 g/m², with plastics accounting for 84.6% of the debris by abundance and 51.7% by weight. The most common items included plastic wrappers, fragments, cups, and bottles. Coastal cleanliness was rated as moderate during both transitional seasons. The findings highlight the influence of ocean currents in transporting debris toward the Pemangkat River estuary and emphasize the urgent need for improved waste management and enhanced public awareness initiatives to address plastic pollution.

INTRODUCTION

Marine debris consists of persistent solid materials that float and are produced either directly or indirectly, ultimately accumulating in the marine environment **(Purba *et al.*, 2019; Van Sebille *et al.*, 2020; Suteja *et al.*, 2021b)**. The influx of marine debris can be attributed to various factors, such as river currents, wind, storms, or ocean currents **(Cordova *et al.*, 2019; Dobler *et al.*, 2022; Iskandar *et al.*, 2022)**. This debris can vary in size, ranging from large objects to microplastics, and can be found in marine environments, including beaches. Both types present complex and significant risks to the health of living organisms, especially marine wildlife **(Pereiro *et al.*, 2019; Suteja *et al.*, 2021b)**.

As noted by **Matthews *et al.* (2017)**, the movement of marine debris on the water's surface generally aligns with the direction of wind and currents. Additionally, the distribution of debris tends to expand as the speed of these environmental forces increases **(Lebreton *et al.*, 2012; Abraham *et al.*, 2022; Dobler *et al.*, 2022; Barry *et al.*, 2023)**.

The investigation of marine debris has emerged as a critical area of research worldwide, including in Indonesia, due to its significant repercussions for marine ecosystems and public health. Among the various forms of marine debris, plastic has been recognized as one of the most pressing environmental challenges **(Cordova *et al.*, 2019; Van Sebille *et al.*, 2020; Suteja *et al.*, 2021a)**. Current estimates indicate that over 5 trillion pieces of plastic, weighing more than 250,000 tons, are present in the oceans, highlighting the vast scale of this issue **(Eriksen *et al.*, 2014)**. Furthermore, microplastics can enter marine environments through multiple pathways, including atmospheric transport **(Purwiyanto *et al.*, 2022)**. This, in turn, complicates the landscape of marine pollution **(Liu *et al.*, 2019)**. This body of research suggests that marine debris is not only the result of direct disposal into the ocean but also stems from more remote sources, thereby complicating management strategies.

In Indonesia, which ranks among the countries with the highest rates of plastic pollution **(Jambeck *et al.*, 2015)**, the significance of this research is becoming increasingly apparent. **Gelcich *et al.* (2014)** emphasized that enhancing public awareness regarding human impacts on marine environments is essential for promoting collective action to tackle this challenge. Studies conducted in Indonesia reveal a general lack of understanding among the public about the effects of marine debris, underscoring the necessity for educational initiatives and heightened awareness **(Tahir *et al.*, 2019)**. For example, research by **Suryono *et al.* (2021)** demonstrated that data collection on the distribution of plastic debris in coastal areas can aid in formulating more effective mitigation strategies. Furthermore, **Yu *et al.* (2023)** highlighted that the surge in plastic production since the 1950s has exacerbated marine pollution, projecting that by 2050, up to 12,000 million metric tons of plastic waste could accumulate in the natural environment. This situation underscores the urgent need for prompt and collaborative action at both global and local levels to address the issue. Research conducted in various regions, including Indonesia, can yield valuable insights into pollution trends and the efficacy of marine debris management strategies.

Various techniques and methodologies have been developed to evaluate the distribution of marine debris. The progression of these methods is vital for comprehending environmental impacts and formulating effective mitigation strategies. These approaches encompass ocean modeling **(Eriksen *et al.*, 2014; Critchell *et al.*, 2015; Pereiro *et al.*, 2019; Miladinova *et al.*, 2020; Iskandar *et al.*, 2021; Dobler *et al.*, 2022; Kisnarti *et al.*, 2024)**, satellite technology **(Martínez-Vicente *et al.*, 2019; Hu, 2021)**, and field observations **(Tahir *et al.*, 2019; Suteja *et al.*, 2021b)**. Integrating sampling techniques, enhanced monitoring technologies, and numerical modeling is crucial for accurately assessing the distribution of marine debris. This comprehensive approach not only facilitates a better understanding of current challenges but also aids in developing more effective strategies to mitigate the adverse effects of marine debris on the environment.

Lemukutan Island is a significant area in Indonesia, recognized as a strategic island and designated as a Marine Conservation Area (MCA) under the Minister of Marine Affairs and Fisheries Regulation Number 31/PERMEN-KP/2020, established in 2020. This designation allows the area to function as a marine conservation zone governed by local authorities, encompassing all stages from planning and designation to management, monitoring, and evaluation. In addition to its conservation role, Lemukutan Island serves as an underwater tourism destination, attracting visitors to experience its marine beauty **(Kuncoro *et al.*, 2023)**. However, the influx of local and international tourists has led to waste management challenges on the island. Moreover, Lemukutan Island's location—directly facing the Karimata Strait and the southern South China Sea **(Apriansyah & Atmadipoera, 2020)**, as well as the Pemangkat and Selakau rivers estuary—makes it susceptible to the accumulation of marine debris along its coastline, as ocean currents transport waste from nearby islands. While the volume and impact of marine debris on Lemukutan Island have not been documented, its presence threatens the sustainability of aquatic biota and the overall environment. An increase in stranded marine debris can adversely affect the food sources for marine organisms, as well as impact the local economy and public health **(Jang *et al.*, 2014; Arabi & Nahman, 2020; Provencher *et al.*, 2020)**. Consequently, there is a pressing need for a comprehensive study to investigate the characteristics and dynamics of marine debris in the ocean and its movement processes.

This research aimed to assess the density and types of marine debris during transition seasons (May and November), which coincide with peak tourist arrivals to Lemukutan Island, significantly influencing the volume of waste generated. Additionally, the study employed the CROCO (Coastal and Regional Ocean Community) model to analyze ocean circulation, utilizing the model's output to trace the origins of the marine debris accumulating on Lemukutan Island.

MATERIALS AND METHODS

1. Study area and field data collections

Lemukutan is a small island located in the southern part of the South China Sea, Bengkayang Regency, West Kalimantan, Indonesia (Fig. 1). It forms part of a cluster of islands around the Karimata Strait and is recognized as both a conservation area and a tourism destination. Geologically, Lemukutan Island covers an area of approximately 5km² and is surrounded by clear waters rich in biological resources including coral reef ecosystems **(Kuncoro *et al.*, 2023)**.

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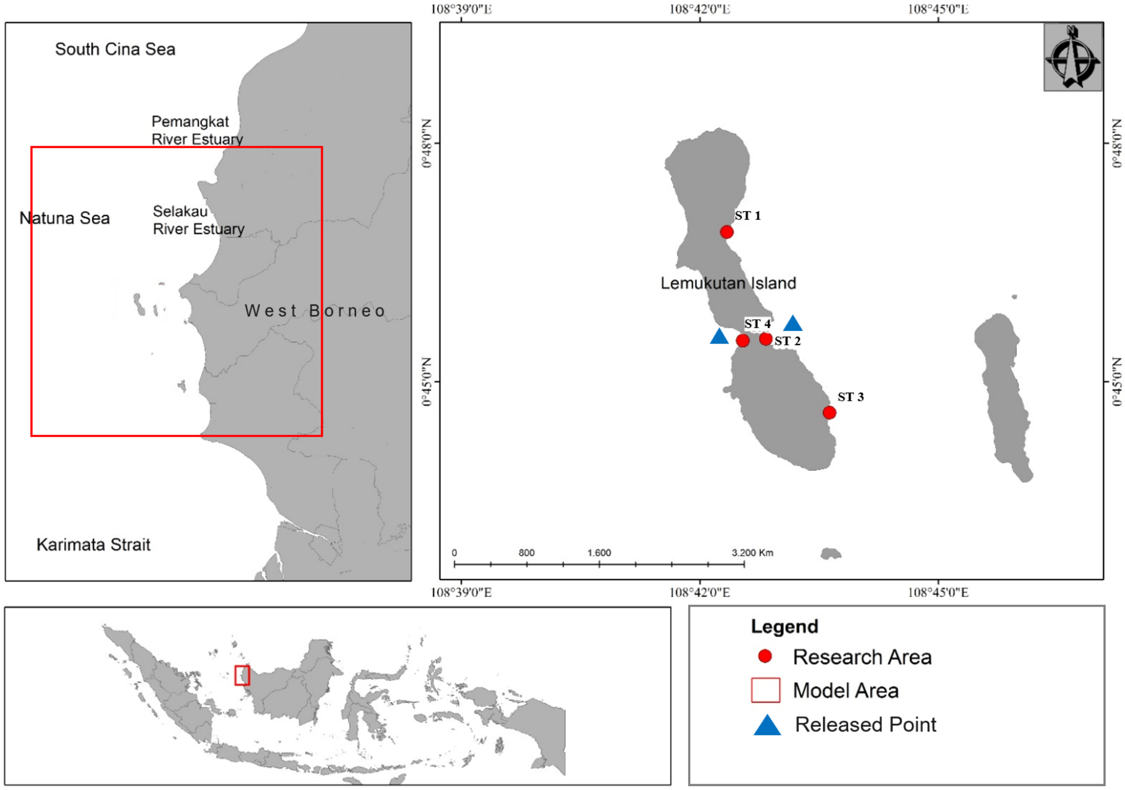

Fig. 1. Domain model (red box) (a) and sampling sites (red dot) for stranded marine debris (b) in waters around Lemukutan Island

In this study, marine debris sampling was conducted in November 2023, corresponding to the second monsoon break. In contrast, sampling for the first monsoon break took place in April–May 2024. The timing was selected based on observations that the period between the first and second monsoon breaks coincides with peak tourist activity on Lemukutan Island, which likely contributes to the increased accumulation of marine debris. Sampling was carried out at four sites on Lemukutan Island (ST1 – Cina Bay, ST2 – Melano Bay, ST3 – Surau Bay, and ST4 – West Melano Bay). These sites were chosen due to their significance as population centers and tourism hubs. Sampling lasted for three hours daily and was conducted during low tide to facilitate observations.

Marine debris on Lemukutan Island was classified as macro debris (2.5– 100cm). This classification was selected because such debris is relatively easy to collect, in addition to being visible, and identifiable, while providing supplementary information during survey activities. The categorization of marine debris followed guidelines adapted from the NOAA program **(Lippiatt *et al.*, 2013)** and UNEP/IOC standards **(Cheshire *et al.*, 2009)**.

Surveys at each site were conducted using a 50m² transect (2 × 25m). Transects were measured with a tape, marked with string, and positioned at the highest tide line, with observations carried out during low tide to aid sampling **(Tramoy *et al.*, 2021)**. Marine debris samples were collected along transects using a visual survey method on the sediment surface **(Suteja *et al.*, 2021b)**. Excavation was performed when any portion of macro debris protruded above the sediment. Each transect survey was repeated at least twice. Observers wore gloves and shoes for safety and to prevent injuries from sharp objects or exposure to hazardous materials such as discarded medical supplies, animal remains/waste, or contraceptives/condoms **(Lippiatt *et al.*, 2013; Suteja *et al.*, 2021b)**. Writing tools were used to document findings *in situ*, and photographs were taken for reference to support later analysis. Collected debris was placed in plastic bags, cleaned, and transported to the laboratory for counting and analysis.

2. The datasets

2.1 Marine debris identification

The identification of marine debris collected from Lemukutan Island followed established guidelines **(Lippiatt *et al.*, 2013; Suteja *et al.*, 2021b)**, using a modified NOAA datasheet. Debris was cleaned with fresh water in the laboratory and air-dried, avoiding direct sunlight. Each item was visually categorized into one of seven groups: plastic, metal, glass, wood, paper, fabric, or other. The "other" category included animal cadavers/waste, food scraps, and unidentified items. These categories were further subdivided into 38 subcategories. After classification, items were weighed using a digital scale (Haser WH-B28, 0.1 g accuracy) and counted with a hand counter (TAGOSHI FH-102).

2.2 Models

The source-tracing approach involved two stages. First, a 3D hydrodynamic model was used to resolve the equations of motion that characterize ocean circulation within the model's domain (Fig. 1a). In the second stage, virtual particles were released into the flow field and allowed to move under the influence of hydrodynamic forces generated by the model's output.

The 3D hydrodynamic model was based on the Coastal and Regional Ocean Community Model (CROCO, version 2.0; https://www.croco-ocean.org) **(Auclair *et al.*, 2022; Penven *et al.*, 2022)**. CROCO, derived from ROMS-AGRIF **(Shchepetkin & McWilliams, 2005)**, has been widely used for ocean circulation studies **(Debreu *et al.*, 2016; Azis Ismail & Ribbe, 2019; Amemou *et al.*, 2020; de Mello *et al.*, 2022; Adhinugraha *et al.*, 2023; Apriansyah *et al.*, 2023a, b; Mogollón *et al.*, 2023)**.

The model configuration for Lemukutan waters used bathymetric data from GEBCO at 15-second resolution **(Weatherall *et al.*, 2015)**, spanning 0.30°N–1.30°N and 108.42°E–109.35°E. It had a horizontal resolution of 1/48° and 32 vertical sigma layers. Initial values and boundary conditions were derived from GLORYS12v1 reanalysis data (Copernicus Marine Environment Monitoring Service). The model was forced with tidal data from TPXO **(Egbert & Erofeeva, 2002)**, river discharge from GLOFAS **(Harrigan *et al.*, 2020)** and atmospheric data from ERA5-ECMWF **(Hersbach *et al.*, 2020)**. CROCO outputs included daily time-series data of sea surface height (SSH), sea surface temperature (SST), and zonal/meridional surface currents.

The 2023 CROCO current velocity outputs were coupled with the Ichthyop v3.3.6 ecosystem model **(Lett *et al.*, 2008)** to trace the origins of marine debris stranded around Lemukutan Island. Ichthyop is an open-source software designed to study the influence of physical and biological processes on the movement of fish larvae while having the potential to simulate particle transport. It accounts for horizontal/vertical movement, dispersion, and buoyancy. Since the CROCO outputs already incorporated wind-driven currents, no additional wind effects were added.

The selection of Ichthyop was based on its successful application in marine debris studies in the Mediterranean Sea **(Macias *et al.*, 2019; Miladinova *et al.*, 2020)**. In this study, we focused on plastic debris—the most abundant type found on Lemukutan Island (see Results and Discussion)—using a density of 0.9g/ cm^3. Direct wind effects and Stokes drift were not considered, as small plastic fragments are generally transported below the surface **(Macias *et al.*, 2019; Miladinova *et al.*, 2020)**. Previous research has shown that surface currents are the dominant driver of debris accumulation **(Kubota, 1994; Martinez *et al.*, 2009)**, while Stokes drift has only minimal influence **(Kubota, 1994)**.

Ichthyop simulates two possible behaviors for particles at coastlines: bouncing or beaching. In the bouncing scenario, particles re-enter the sea after reaching the shoreline and continue moving. In the beaching scenario, particles remain stranded once they reach the shore and are tracked as beached until the end of the simulation.

In this study, four scenarios were conducted (Table 1). A total of 1,000 virtual particles (representing plastic debris) were released from the western and eastern coasts of Lemukutan Island (Fig. 1b) during the first monsoon break (February–May) and the second monsoon break (August–November). Using a backward-tracing method, we tracked debris movement for 30 days. The final positions of particles on day 30 were interpreted as the potential sources of marine debris stranded on the island.

Table 1. Scenario setting

Scenario name	Release zone	Coastal behavior	Periods of simulation
L1-B	Western part of the island	Bouncing	Feb to May
L1-T	Eastern part of the island	Bouncing	Feb to May
L2-B	Western part of the island	Bouncing	Aug to Nov
L2-T	Eastern part of the island	Bouncing	Aug to Nov

2. Data analysis

The density (D) of marine debris is determined by comparing the total number of items (N) and their weight to the area of the transect (A) using the following formula **(Terzi & Seyhan, 2017)**:

$$D = N / A$$

The area (A) is determined by multiplying the length (m) by the width (m) of the transect during the sampling. The density of marine debris is present in items per square meter (items/m^2) and weight per square meter (weight/m^2). Additionally, we evaluated the cleanliness of 4 beaches located on Lemukutan Island by utilizing the Clean-Coast Index (CCI), as referenced in earlier studies **(Terzi & Seyhan, 2017; Suteja *et al*., 2021b)**. The CCI was determined as follows:

$$CCI = D \, x \, K$$

The D represents the density of stranded marine debris measured in items per square meter (items/m^2), while K is a correction coefficient set at 20. This coefficient is utilized to enhance the clarity of the results for public understanding. According to the CCI formula, beaches are categorized into five primary classifications: very clean (indicating no visible marine debris, 0 – 2), clean (large areas without marine debris, 2 – 5), moderate (presence of recognizable marine debris, 5 – 10), dirty (significant amounts of marine debris, 10 – 20), and very dirty (marine debris predominantly covers the beaches area, >20). The CCI serves as an indicator for assessing the pollution levels on these beaches **(Vlachogianni *et al*., 2018; Mugilarasan *et al*., 2021).**

RESULTS

1. The density of marine debris

In this study, 963 marine debris items were identified, with a cumulative weight of 9966g. The average debris density recorded was 4.4 ± 0.08 item/m^2, while the average weight density was 22.3 ± 0.46g/ m^2. Sampling was conducted at four distinct stations, with observations in May and November representing the first and second transition seasons. In November, 419 debris items were collected, weighing 4787g, whereas in May, the total debris increased to 544 items with a weight of 5179g.

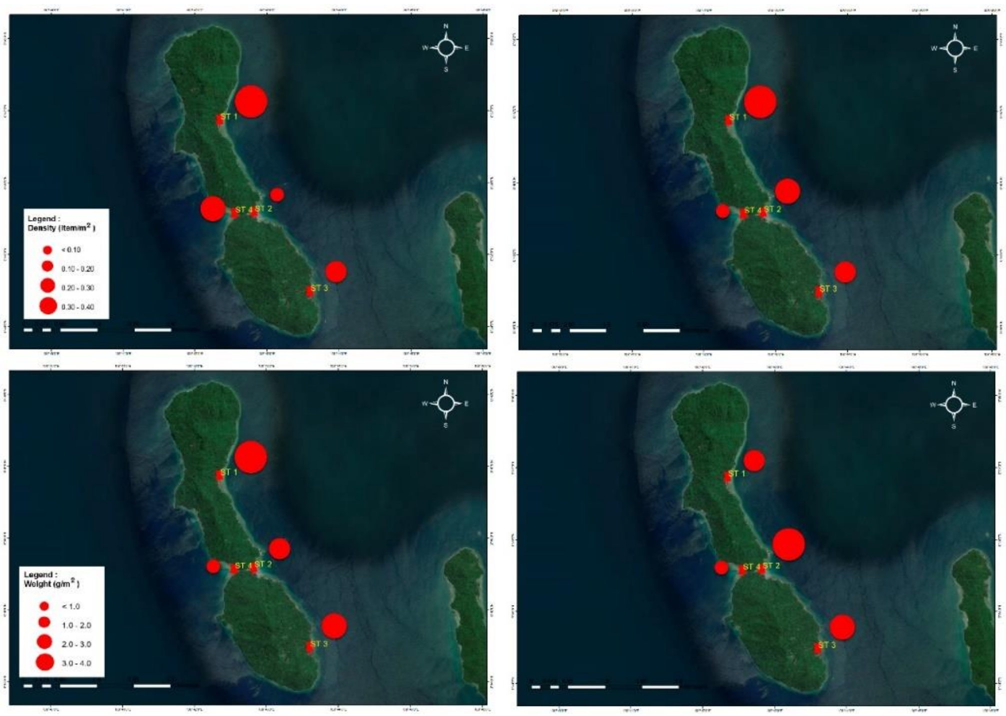

Fig. 2. Marine debris is classified according to density (upper panels) and weight (lower panels) in the second break monsoon (left panels) and the first break monsoon (right panels).

The highest density of stranded marine debris was observed at Cina Bay, with 0.32 items/m² during the second monsoon break and 0.34 items/m² during the first monsoon break (Fig. 2, upper panels). This elevated density is attributed to the combined effects of intensive tourism activities—which increase local waste generation—and ocean currents transporting debris from the north, resulting in greater accumulation compared to other sites on Lemukutan Island.

Conversely, the lowest debris densities were recorded at West Melano Bay (0.17 items/m²) during the first monsoon break and at Melano Bay (0.13 items/m²) during the second monsoon break (Fig. 2, upper panels).

Field observations further revealed that the highest weight of stranded marine debris occurred at Cina Bay (4.04g/ m²) during the second monsoon break and at Melano Bay (3.14g/ m²) during the first monsoon break. The lowest weights were recorded at West Melano Bay, with 0.13g/ m² during the second monsoon break and 1.27g/ m² during the first monsoon break. Meanwhile, Surau Bay recorded 2.75 and 2.25g/ m^2 during the second and first monsoon breaks, respectively (Fig. 2, lower panel).

2. Category of marine debris

Marine debris collected from the four sampling sites on Lemukutan Island was classified into six main categories and 38 subcategories. This classification provided detailed insights into the types of debris stranded on the island’s shores during the sampling periods, which coincided with peak tourist activity.

Across both periods, plastics were the dominant debris category, accounting for 84.6% of total items, followed by metals (4.5%), fabrics/textiles (3.8%), glass (3.7%), wood/paper (2.9%), and other materials (0.6%) (Fig. 3, upper panel). In terms of weight, the ranking differed: plastics (51.7%) were most prevalent, followed by fabrics/textiles (23.3%), glass (14.3%), metals (7.4%), wood/paper (2.0%), and other materials (1.3%).

Plastic debris subcategories included bottles, balls, cosmetic and bathing wraps, medicine wraps, plastic bags, thick plastic packaging, cups, food containers and spoons, miscellaneous fragments, pipes and hoses, straws, footwear, Styrofoam, ropes and fishing gear, and plastic lids.

When assessed by season, plastics remained dominant. During the second monsoon break, debris abundance consisted of plastics (84.8%), metals (5.3%), glass (4.1%), fabrics/textiles (4.3%), and other materials (1.4%); no wood/paper was recorded. In contrast, during the first monsoon break, the composition was plastics (84.4%), metals (3.9%), glass (3.3%), wood/paper (5.1%), fabrics/textiles (3.3%), and no other materials.

In terms of weight, the composition during the second monsoon break was plastics (43.2%), metals (10.2%), glass (14.9%), fabrics/textiles (29.1%), and other materials (2.7%); no wood/paper was recorded. During the first monsoon break, the weight composition was plastics (59.6%), metals (4.8%), glass (13.8%), wood/paper (3.9%), fabrics/textiles (17.9%), and no other materials (Fig. 3, lower panel).

Overall, the results demonstrate that plastic constitutes the predominant form of marine debris across all sampling sites and periods on Lemukutan Island, totaling 810 items (0.270 items/m^2) and weighing 5,156 g (1.719 g/m^2).

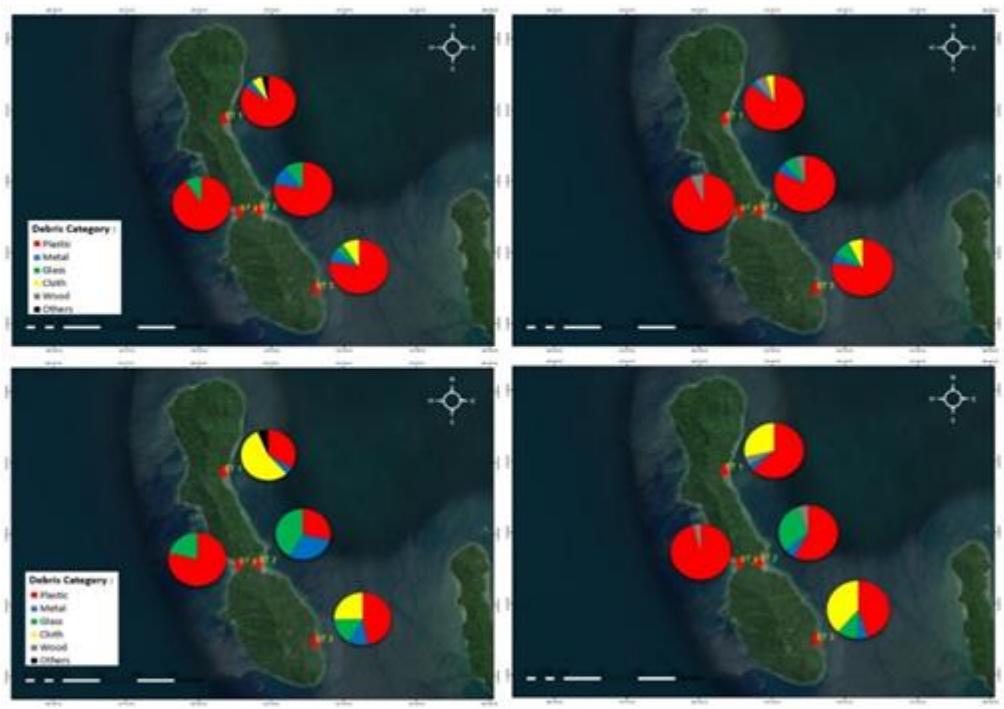

Fig. 3. The marine debris category according to density (upper panels) and weight (lower panels) in the second break monsoon (left panels) and the first break monsoon (right panels)

3. Clean-coastal index (CCI)

The Clean-Coast Index (CCI) values revealed differences in cleanliness levels among the four regions of Lemukutan Island during the two transitional seasons (Fig. 4). Cina Bay (Station 1) recorded the highest marine debris accumulation, resulting in a moderate classification. Similarly, Melano Bay (Station 2) and West Melano Bay (Station 4) were also classified as moderate, whereas Surau Bay (Station 3) consistently fell under the clean category. These variations reflect differing environmental pressures and the relative effectiveness of waste management in each area.

The overall mean CCI value across all sites was 5.16 ± 5.85, corresponding to a moderate classification, which suggests that only limited amounts of marine debris were present. Seasonal averages showed CCI values of 3.53 ± 7.77 during the second monsoon break and 2.75 ± 8.00 during the first monsoon break, both classified as moderate. These seasonal trends are strongly influenced by increased human activities, particularly the surge in tourist visits and coastal activities leading up to year-end holidays.

According to **Alkalay *et al.* (2007)**, beaches can be classified on a scale ranging from very dirty to very clean, representing a continuum from high levels of stranded debris to the near absence of visible waste across large coastal areas. Based on this scale, Lemukutan Island’s coastal regions were categorized as moderate and clean. During the second monsoon break, the classification percentages were: very dirty (0.0%), dirty (15.5%), moderate (84.6%), clean (0.0%), and very clean (0.0%). During the first monsoon break, the percentages were: very dirty (0.0%), dirty (58.6%), moderate (41.4%), clean (0.0%), and very clean (0.0%).

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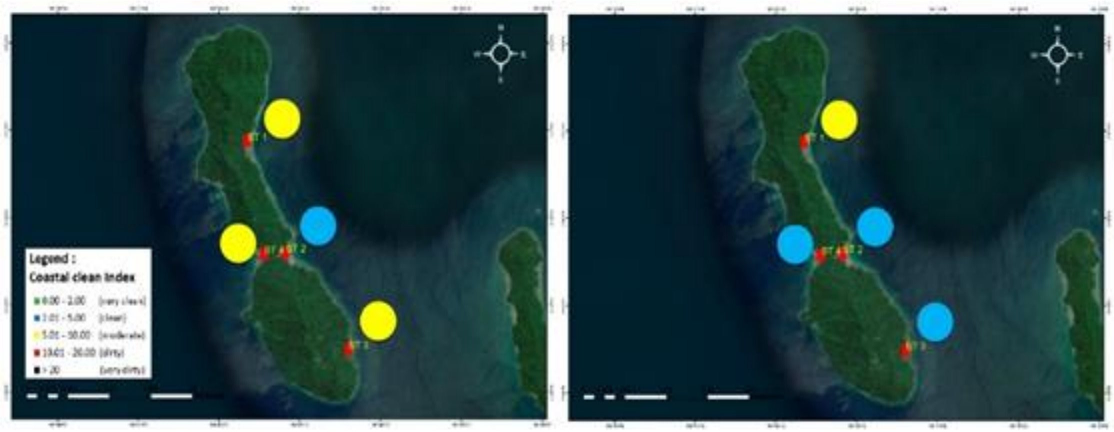

Fig. 4. Coastal clean index in the second break monsoon (left panels) and the first break monsoon (right panels)

During the first measurement period (the second monsoon break), Cina Bay (Station 1) recorded the highest marine debris accumulation (Fig. 2, upper left panel). Consequently, its Clean-Coast Index (CCI) was classified as moderate, reflecting the presence of noticeable debris. During this season, Melano Bay (Station 3) and West Melano Bay (Station 4) were also categorized as moderate, while Surau Bay (Station 2) was the only site classified as clean, indicating minimal debris accumulation (Fig. 2, left panel). In the second measurement period, all sampling sites, except Cina Bay, were classified as clean (Fig. 4, right panel). Cina Bay remained the only location with a moderate classification.

4. Near-surface circulation and trajectory analysis

Before presenting the results of the marine debris simulation scenarios, it is important to describe the circulation dynamics in the waters surrounding Lemukutan Island. This area is part of the Natuna/South China Sea **(Apriansyah & Atmadipoera, 2020; Kok *et al.*, 2021; Apriansyah *et al.*, 2022)**, where seasonal variations in circulation and oceanographic parameters are primarily driven by wind-induced processes **(Kushadiwijayanto *et al.*, 2017)**. Other influencing factors include seabed topography, tidal forcing **(Kushadiwijayanto *et al.*, 2017)**, and freshwater discharge from the Pemangkat and Selakau rivers. However, the specific effects of these riverine inputs on the circulation around Lemukutan Island have not yet been investigated. Overall, the circulation patterns in this region are complex, with dominant currents generally following a north–south orientation.

During the early west monsoon (February; Fig. 5a), the prevailing current flows southward from the north, continuing southwestward into the Karimata Strait. In the first transitional season (May; Fig. 5b), currents originate from the north and northeast and move toward the southwest. However, they weaken and shift southward after passing Lemukutan Island and its vicinity before eventually entering the Karimata Strait.

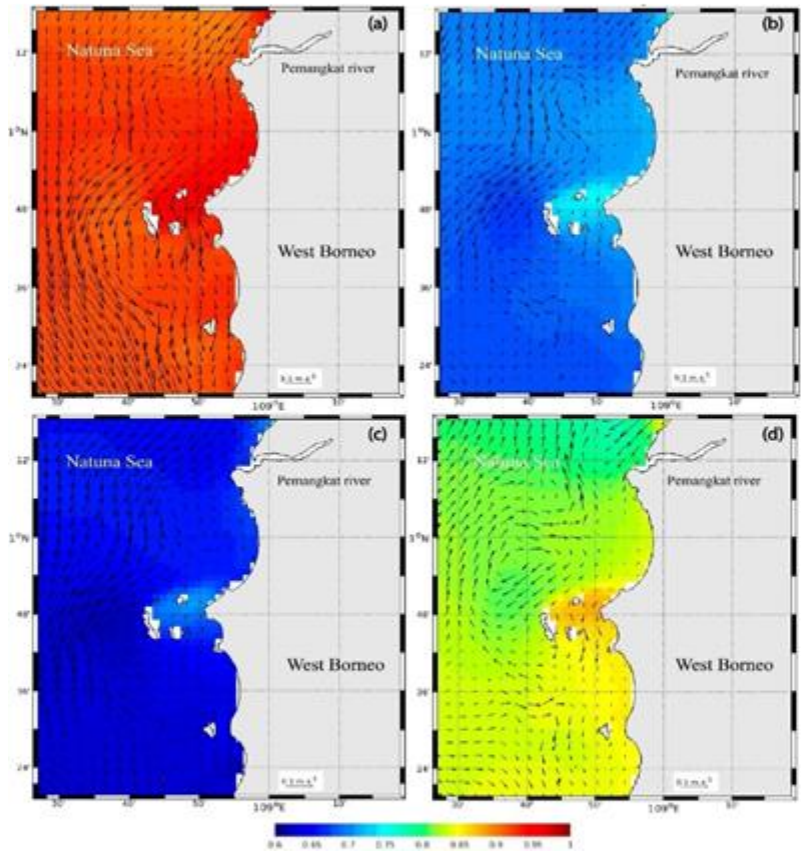

Fig. 5. The Lemukutan Island waters circulation based on the monthly mean velocity vector over the upper 5m in different months: (a) February, (b) May, (c) August, and (d) November

During the east monsoon period (August; Fig. 5c), the current pattern around Lemukutan Island generally flows from the northeast toward the southwest before being redirected southward into the Karimata Strait at relatively weak velocities. In the second transitional season (November; Fig. 5d), current speeds weaken further, with part of the flow diverted northward into the South China Sea.

The trajectory simulations were derived from the processed outputs of the CROCO model and implemented in Ichthyop, using horizontal current parameters (*u, v*). Particle release points were positioned at two sampling coordinates: 0.78°N, 108.72°E (eastern Lemukutan Island; scenarios L1-T and L2-T) and 0.75°N, 108.69°E (western Lemukutan Island; scenarios L1-B and L2-B). These locations were selected based on the presence of stranded marine debris observed on both sides of the island, raising important questions about its sources.

Since plastics were the predominant debris type identified in this study (see subsection 3.2), a total of 1,000 virtual particles were released from both the eastern and western sites at a depth of 0.5m. The simulations assumed that particle transport occurred primarily through horizontal advection.

A backward-tracing approach was applied, whereby particles were released and tracked for 30 days to identify their potential origins. The detailed setup of the four scenarios is presented in Table (1), covering both the first and second transitional seasons.

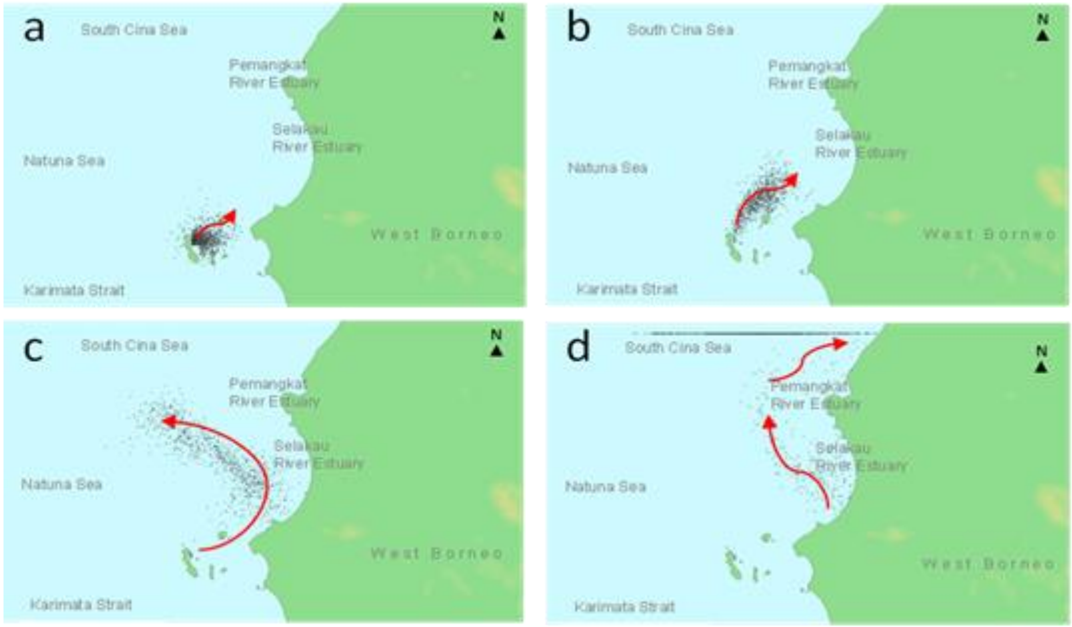

Fig. 6. The particle trajectory patterns (L1-B) during the first transitional season on days (a) 1, (b) 10, (c) 20, and (d) 30

The trajectory simulation results demonstrate that the current patterns around Lemukutan Island are consistent with the circulation model. The transport of plastic waste particles, whether released from the eastern side (Fig. 6) or the western side (Fig. 7) in May, generally originated from the northeast. On day 1, particles moved from the northern coast of Lemukutan Island toward the northeast, with some appearing to originate along the island's shoreline. By day 10, particles were dispersed across the northern and northwestern areas. By day 20, they were more evenly distributed, primarily from the northwest. By day 30, particle transport again shifted to the northeast, with many directed toward the Pemangkat River estuary.

Overall, the distribution patterns of plastic waste particles released from the western side closely mirrored those from the eastern side, indicating consistent transport pathways dominated by northeastward currents.

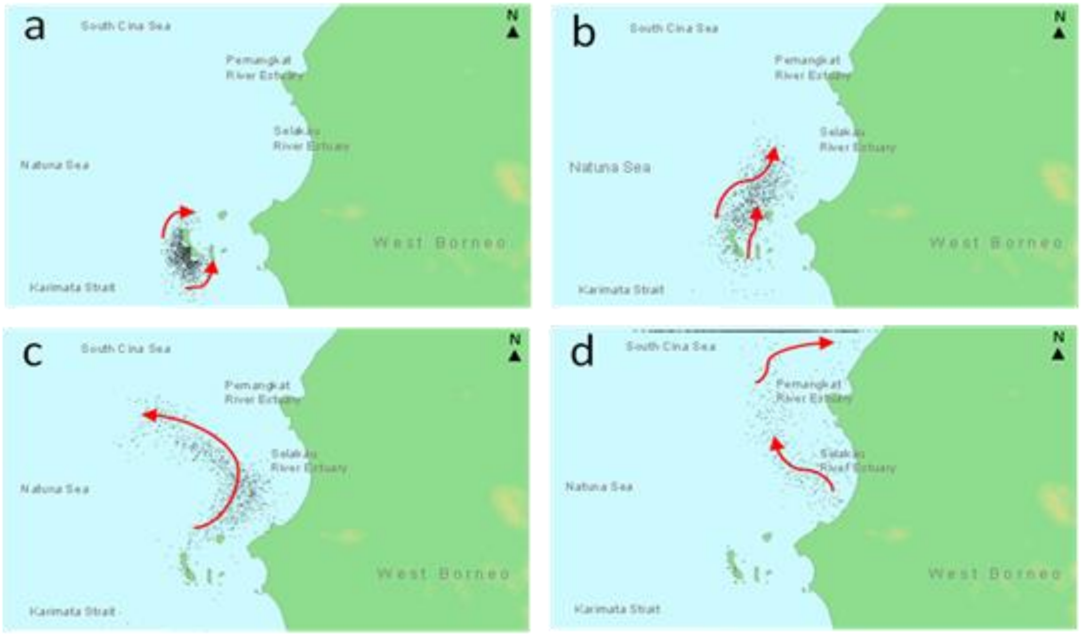

Fig. 7. The particle trajectory patterns (L1-T) during the first transitional season on days (a) 1, (b) 10, (c) 20, and (d) 30

Fig. 8. The particle trajectory patterns (L2-B) during the second transitional season on days (a) 1, (b) 10, (c) 20, and (d) 30

The plastic waste particles released in November generally move from the northeast direction. On the first day, the particles originate from the northeast, with some coming from Kabung Island and Big Penata Island. After 10 days, the plastic waste particles begin to spread, with some originating from the coastline of West Kalimantan and others dispersing from the northwest. By the 20th day, the distribution of plastic waste particles becomes more uniform.

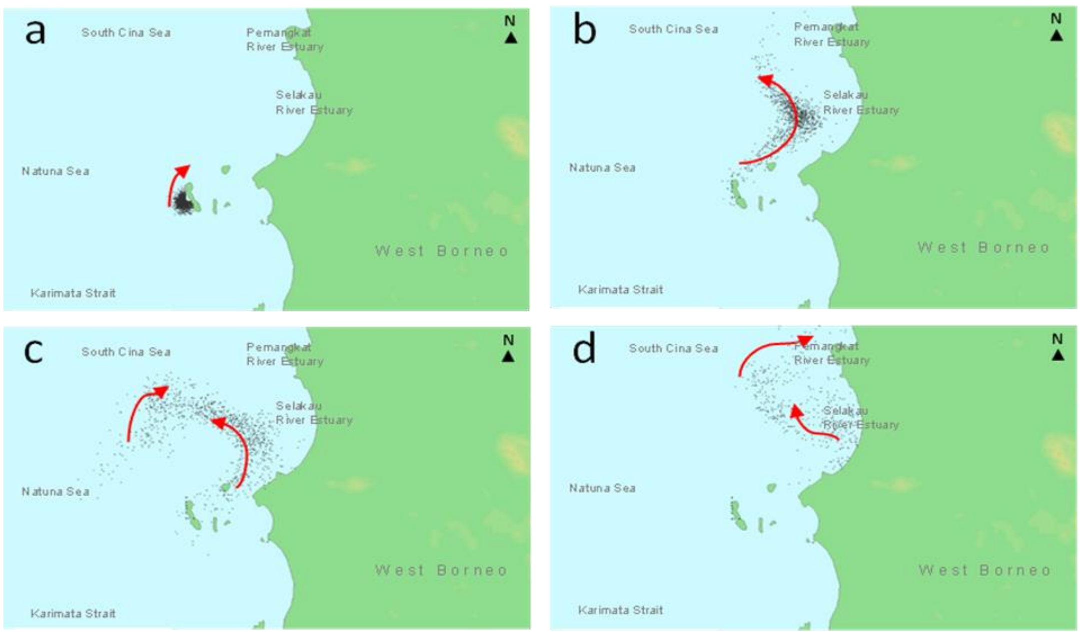

Fig. 9. The particle trajectory patterns (L2-T) during the second transitional season on days (a) 1, (b) 10, (c) 20, and (d) 30

On the 30th day, the plastic waste particles from the northeast are spread from Singkawang to Pemangkat, with a river in Pemangkat suspected to be one of the sources of plastic waste. The distribution pattern of plastic waste particles in the western part (Fig. 8) exhibits a similar pattern to that of the eastern part (Fig. 9), characterized by a bifurcated pattern forming from the north and south, with the overall dispersion primarily originating from the northeast. This observation highlights the interconnectedness of the marine debris dynamics in the region, emphasizing the influence of local geographical features and currents on the movement of plastic waste.

DISCUSSION

1. The density of marine debris

We suspect that the high density of marine debris in Cina Bay is linked to intensive human activities and tourism, which act as major local sources of waste. In terms of proximity, Cina Bay is also the closest site to the Pemangkat River. Previous studies have shown that rivers and settlements are significant contributors of debris to aquatic environments **(Cordova & Nurhati, 2019; Iskandar *et al.*, 2021; Dobler *et al.*, 2022)**. This situation is further exacerbated by the harmful impacts of debris, which can physically injure aquatic organisms (e.g., digestive tract blockage, mechanical damage) and also act as vectors for toxic pollutants that accumulate through the food chain **(Noor *et al.*, 2025; Purnama *et al.*, 2025; Sadiq & Al-Hejuje, 2025)**. Unfortunately, debris emissions from the Pemangkat River—and from other rivers in West Kalimantan—have not yet been quantified, warranting further study. Globally, **Lebreton *et al.* (2017)**

estimated that at least 2.4 million tonnes of plastic waste enter marine systems annually from land, with rivers acting as major conduits of marine debris. Evidence from Indonesia confirms that national rivers significantly increase marine debris loads **(Cordova & Nurhati, 2019; Dobler *et al.*, 2022)**. Furthermore, estuarine dynamics play a role in debris retention: macro debris can be temporarily trapped in river estuaries by tidal forces **(van Emmerik *et al.*, 2020)** before being flushed into the sea under stronger flows or low tide conditions **(Lorenzi *et al.*, 2020; van Emmerik *et al.*, 2020)**.

Conversely, beaches located far from settlements and with low tourism activity, such as West Melano Bay, displayed minimal debris accumulation. In such areas, potential waste input from human populations is reduced. This aligns with findings by **Hardesty *et al.* (2017)**, who reported a strong correlation between marine debris density and local population size.

Two key factors drive higher debris weights at Cina Bay and Melano Bay: dense tourism activities and higher population concentrations. Tourism, in particular, strongly influences debris accumulation. This trend has been corroborated by research conducted in Geoje Island, South Korea **(Jang *et al.*, 2014)**; along the South China Sea **(Zhao *et al.*, 2015)**; the Great Barrier Reef, Australia **(Wilson & Verlis, 2017)**; Tidung Island, Indonesia **(Hayati *et al.*, 2020)**; and Bali, Indonesia **(Suteja *et al.*, 2021b)**. Similarly, studies in Australia established a strong link between debris accumulation and local population density **(Hardesty *et al.*, 2017; Horpet *et al.*, 2021)**. In contrast, West Melano Bay recorded the lowest weights (0.13g/ m^2 during the second monsoon break and 1.27g/ m^2 during the first), reflecting limited tourism and sparse populations **(Adu-Boahen, 2024)**.

This study further revealed that during the second monsoon break, the ranking of stranded debris weights was: Melano Bay < Surau Bay < West Melano Bay < Cina Bay. In the first monsoon break, the ranking was: West Melano Bay < Surau Bay < Melano Bay < Cina Bay. These results confirm that Cina Bay and Melano Bay represent the primary hotspots for debris accumulation on Lemukutan Island. Overall, debris weight was significantly correlated with debris abundance.

2. Category of marine debris

This outcome aligns with the global rise in plastic consumption, which reached 368 million tonnes annually in 2019 **(PlasticsEurope, 2020; Zhang, 2021)**. On Lemukutan Island, the most frequently observed debris types were plastic wrappers (21.1%), plastic fragments (16.3%), plastic cups (15.3%), and plastic bottles (12.5%). This composition provides new insights into debris subcategories during the transitional season. It contrasts slightly with findings from **Suteja *et al.* (2021b)**, where plastic bags, straws, and cups dominated. In addition, current findings contradict observations from nine rivers discharging into Jakarta Bay, where styrofoam was the most common plastic type **(Cordova & Nurhati, 2019)**.

3. Clean-coast index (CCI)

Cina Bay hosts numerous homestays and serves as the island's main docking area, acting as a gateway for visitors **(Kushadiwijayanto *et al.*, 2017; Apriansyah & Atmadipoera, 2020; Rudianto *et al.*, 2020)**. Its northern position makes it the first coastal zone to receive currents from the Natuna Sea/South China Sea **(Kushadiwijayanto *et al.*, 2017; Apriansyah & Atmadipoera, 2020)**, thereby increasing its potential as a debris accumulation site. The heavy accumulation observed here during both sampling periods poses a risk to local tourism.

Tourists strongly associate beach cleanliness with destination attractiveness, influencing perceptions of safety, comfort, and overall appeal **(Hardesty *et al.*, 2017; Wilson & Verlis, 2017)**. Clean environments tend to attract more visitors and improve tourist satisfaction, whereas polluted beaches can deter travel and harm local economies. This highlights the need for government, communities, and stakeholders to strengthen waste management and raise awareness. Beaches that maintain a clean status year-round are likely to see increased tourism, whereas dirty beaches deter visitors. Empirical research confirms that cleanliness is a critical determinant of destination selection, with cleaner beaches linked to higher revenues **(Tuda *et al.*, 2019; Williams *et al.*, 2020)**, while polluted beaches decrease visitor satisfaction and repeat tourism **(Jang *et al.*, 2021)**.

The CCI results from this study indicate that Lemukutan Island's beaches are cleaner than those of South China Sea beaches **(Zhao *et al.*, 2015)**, the eastern Chinese coastline **(Fahrenfeld *et al.*, 2019)**, the southwestern Luzon coast in the Philippines **(Paler *et al.*, 2019)**, Tidung Island **(Hayati *et al.*, 2020)**, Penang Beach, Malaysia **(Fauziah *et al.*, 2021)**, and southern Bali **(Suteja *et al.*, 2021b)**. Variations in CCI are influenced by multiple factors, including industrial activity, river discharge, runoff, population dynamics, tourist volume, seasonal patterns, waste management practices, and coastal geomorphology **(Vlachogianni *et al.*, 2018; Chen *et al.*, 2020; Mghili *et al.*, 2020; Mugilarasan *et al.*, 2021)**.

4. Near-surface circulation and trajectory analysis

Trajectory simulations confirm that the movement of plastic debris released from Lemukutan Island is strongly influenced by ocean currents, with debris predominantly transported toward the Pemangkat River estuary. This highlights the estuary as a critical pathway for plastic pollution into surrounding waters. Strengthening monitoring and waste management along the Pemangkat River is therefore essential, alongside fostering collaboration between government agencies and local communities to mitigate riverine plastic inputs.

Equally important is the implementation of educational initiatives to enhance public awareness of the ecological and socio-economic impacts of marine debris. Such efforts can promote environmental stewardship, reduce waste accumulation, and support the development of more effective and sustainable policies for marine ecosystem management.

CONCLUSION

This study effectively identified the abundance and characteristics of marine debris washed ashore at four coastal locations on Lemukutan Island, Indonesia, while also assessing the origins of this debris through a numerical modeling approach. The findings revealed that both the geographical positioning of the coastline in relation to the surrounding waters and the increasing activities associated with residents and tourism significantly impact the prevalence of marine debris. Notably, plastic debris emerged as the most common type of marine waste, dominating both in terms of quantity and weight. The research utilized the Coastal Cleanliness Index (CCI) to evaluate the environmental conditions, highlighting the need for regular coastal cleanup initiatives during the transitional seasons. Furthermore, the ocean circulation model demonstrated the critical role of ocean currents in the distribution of plastic debris, pinpointing the estuary of the Pemangkat River as a significant potential source of pollution. This study underscores the urgent need to enhance waste monitoring and management practices, as well as to promote collaboration between governmental agencies and local communities to address the sources of plastic waste. Additionally, it emphasizes the importance of educational initiatives aimed at increasing public awareness of the impacts of plastic pollution, which are vital for supporting conservation efforts and fostering sustainable environmental management on Lemukutan Island.

REFERENCES

Abraham, M.T.; Satyam, N.; Pradhan, B. and Tian, H. (2022). Debris flow simulation 2D (DFS 2D): Numerical modelling of debris flows and calibration of friction parameters. J. Rock Mech. Geotech. Eng., 14, 1747–1760.

Adhinugraha, F.A.C.; Atmadipoera, A.S. and Hartanto, M.T. (2023). The ocean response to El Nino Southern Oscillation (ENSO) in the Bali Sea: a model study, in: IOP Conference Series: Earth and Environmental Science.

Adu-Boahen, K. (2024). Investigation of Abundance and Spatial Distribution of Marine Debris on Ghanaian Urban Coastal Beaches. J. Environ. Geogr., 17, 29–44.

Alkalay, R.; Pasternak, G. and Zask, A. (2007). Clean-coast index-A new approach for beach cleanliness assessment. Ocean Coast. Manag., 50, 352–362.

Amemou, H.; Koné, V.; Aman, A. and Lett, C. (2020). Assessment of a Lagrangian model using trajectories of oceanographic drifters and fishing devices in the Tropical Atlantic Ocean. Prog. Oceanogr.

Apriansyah. and Atmadipoera, A.S. (2020). Seasonal variation of the Sunda Shelf Throughflow, in: IOP Conference Series: Earth and Environmental Science.

Apriansyah.; Atmadipoera, A.S.; Jaya, I.; Nugroho, D. and Akhir, M.F. (2023a). An Evaluation of a 1/18° Resolution Regional Ocean Circulation Model of CROCO in the Southern Sunda Shelf. Ilmu Kelaut. Indones. J. Mar. Sci., 28, 12–26.

Apriansyah.; Atmadipoera, A.S.; Jaya, I.; Nugroho, D. and Akhir, M.F. (2022). Seasonal oceanographic changes and their implications for the abundance of small pelagic fishes in the southern South China Sea. Reg. Stud. Mar. Sci., 54, 102499.

Apriansyah.; Atmadipoera, A.S.; Nugroho, D.; Jaya, I. and Akhir, M.F. (2023b). Simulated seasonal oceanographic changes and their implication for the small pelagic fisheries in the Java Sea, Indonesia. Mar. Environ. Res., 188, 106012.

Arabi, S. and Nahman, A. (2020). Impacts of marine plastic on ecosystem services and economy: State of South African research. S. Afr. J. Sci., 116.

Auclair, F.; Benshila, R.; Bordois, L.; Boutet, M.; Brémond, M.; Caillaud, M.; Cambon, G.; Capet, X.; Debreu, L.; Ducousso, N.; Dufois, F.; Dumas, F.; Ethé, C.; Gula, J.; Hourdin, C.; Illig, S.; Jullien, S.; Corre, M. Le, Gac, S. Le, Gentil, S. Le, Lemarié, F.; Marchesiello, P.; Mazoyer, C.; Morvan, G.; Nguyen, C.; Penven, P.; Person, R.; Pianezze, J.; Pous, S.; Renault, L.; Roblou, L.; Sepulveda, A.; Theetten, S. (2022). Coastal and Regional Ocean Community model.

Azis Ismail, M.F. and Ribbe, J. (2019). On the cross-shelf exchange driven by frontal eddies along a western boundary current during austral winter 2007. Estuar. Coast. Shelf Sci., 227.

Barry, P.J.; Beraud, C.; Wood, L.E. and Tidbury, H.J. (2023). Modelling of marine debris pathways into UK waters: Example of non-native crustaceans transported across the Atlantic Ocean on floating marine debris. Mar. Pollut. Bull., 186.

Chen, H.; Wang, S.; Guo, H.; Lin, H. and Zhang, Y. (2020). A nationwide assessment of litter on China’s beaches using citizen science data. Environ. Pollut., 258.

Cheshire, A.; Adler, E.; Barbière, J.; Cohen, Y.; Evans, S.; Jarayabhand, S.; Jeftic, L.; Jung, R.-T.; Kinsey, S.; Kusiu, E.T.; Lavine, I.; Manyara, P.; Oosterbaan, L.; Pereira, M.A.; Sheavly, S.; Tkalin, A.; Varadarajan, S.; Wenneker, B. and Westphalen, G. (2009). UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter. Regional Seas Reports and Studies No. 186. IOC Technical Series No. 83, United Nations Environmental Programme / Intergovernmental Oceanographic Commission.

Cordova, M.R. and Nurhati, I.S. (2019). Major sources and monthly variations in the release of land-derived marine debris from the Greater Jakarta area, Indonesia. Sci. Rep., 9.

Cordova, M.R.; Purwiyanto, A.I.S. and Suteja, Y. (2019). Abundance and characteristics of microplastics in the northern coastal waters of Surabaya, Indonesia. Mar. Pollut. Bull., 142, 183–188.

Critchell, K.; Grech, A.; Schlaefer, J.; Andutta, F.P.; Lambrechts, J.; Wolanski, E. and Hamann, M. (2015). Modelling the fate of marine debris along a complex shoreline: Lessons from the Great Barrier Reef. Estuar. Coast. Shelf Sci., 167, 414–426.

de Mello, C.; Barreiro, M.; Ortega, L.; Trinchin, R. and Manta, G. (2022). Coastal upwelling along the Uruguayan coast: Structure, variability and drivers. J. Mar.

Syst. 230.

Debreu, L.; Auclair, F.; Benshila, R.; Capet, X.; Dumas, F.; Julien, S. and Marchesiello, P. (2016). Multiresolution in CROCO (Coastal and Regional Ocean Community model). EGU Gen. Assem. Conf. Abstr., 18, EPSC2016–15272.

Dobler, D.; Maes, C.; Martinez, E.; Rahmania, R.; Gautama, B.G.; Farhan, A.R. and Dounias, E. (2022). On the Fate of Floating Marine Debris Carried to the Sea through the Main Rivers of Indonesia. J. Mar. Sci. Eng., 10.

Egbert, G.D. and Erofeeva, S.Y. (2002). Efficient inverse modeling of barotropic ocean tides. J. Atmos. Ocean. Technol., 19, 183–204.

Eriksen, M.; Lebreton, L.C.M.; Carson, H.S.; Thiel, M.; Moore, C.J.; Borerro, J.C.; Galgani, F.; Ryan, P.G. and Reisser, J. (2014). Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. PLoS One 9.

Fahrenfeld, N.L.; Arbuckle-Keil, G.; Naderi Beni, N.; Bartelt-Hunt, S.L.; De Villiers, S.; Prata, J.C.; da Costa, J.P.J.P.; Lopes, I.; Duarte, A.C.; Rocha-Santos, T.; Madhusudana Rao, B.; Hanke, U.M.; Ward, C.P.; Reddy, C.M.; Cox, K.D.; Covernton, G.A.; Davies, H.L.; Dower, J.F.; Juanes, F.; Dudas, S.E.; Picó, Y.; Barceló, D.; Battulga, B.; Kawahigashi, M.; Oyuntsetseg, B.; González-Pleiter, M.; Tamayo-Belda, M.; Pulido-Reyes, G.; Amariei, G.; Leganés, F.; Rosal, R.; Fernández-Piñas, F.; Blair, R.M.; Waldron, S.; Phoenix, V.R.; Gauchotte-Lindsay, C.; Fischer, M.; Scholz-Böttcher, B.M.; Hu, D.; Shen, M.; Zhang, Y.Y.Y.Y.Y.; Li, H.; Zeng, G.; Wu, N.; Zhang, Y.Y.Y.Y.Y.; Zhang, X.X.; Zhao, Z.; He, J.; Li, W.; Ma, Y.Y.; Niu, Z.; da Costa, J.P.J.P.; Paço, A.; Santos, P.S.M.; Duarte, A.C.; Rocha-Santos, T.; Adam, V.; Yang, T.; Nowack, B.; Rochman, C.M.; Brookson, C.; Bikker, J.; Djuric, N.; Earn, A.; Bucci, K.; Athey, S.; Huntington, A.; McIlwraith, H.; Munno, K.; Frond, H. De, Kolomijeca, A.; Erdle, L.; Grbic, J.; Bayoumi, M.; Borrelle, S.B.; Wu, T.; Santoro, S.; Werbowski, L.M.; Zhu, X.; Giles, R.K.; Hamilton, B.M.; Thaysen, C.; Kaura, A.; Klasios, N.; Ead, L.; Kim, J.; Sherlock, C.; Ho, A.; Hung, C.; Panno, S. V.; Kelly, W.R.; Scott, J.; Zheng, W.; McNeish, R.E.; Holm, N.; Hoellein, T.J.; Baranski, E.L.; Yin, L.; Jiang, C.; Wen, X.; Du, C.; Zhong, W.; Feng, Z.; Long, Y.; Ma, Y.Y.; Triebskorn, R.; Braunbeck, T.; Grummt, T.; Hanslik, L.; Huppertsberg, S.; Jekel, M.; Knepper, T.P.; Krais, S.; Müller, Y.K.; Pittroff, M.; Ruhl, A.S.; Schmieg, H.; Schür, C.; Strobel, C.; Wagner, M.; Zumbülte, N.; Köhler, H.R.; Wang, M.H.; He, Y.; Sen, B.; Fan, Y.; Zheng, K.; Zhu, Z.; Chen, G.; Peng, X.; Jiang, C.; Yin, L.; Li, Z.; Wen, X.; Luo, X.; Hu, S.; Yang, H.H.; Long, Y.; Deng, B.; Huang, L.; Liu, Y.Y.; Zhang, K.; Chen, X.; Xiong, X.; Ruan, Y.; Zhou, H.; Wu, C.; Lam, P.K.S.; Dikareva, N.; Simon, K.S.; Barnes, S.J.; Peixoto, D.; Pinheiro, C.; Amorim, J.; Oliva-Teles, L.; Guilhermino, L.;

Vieira, M.N.; Ariza-Tarazona, M.C.; Villarreal-Chiu, J.F.; Barbieri, V.; Siligardi, C.; Cedillo-González, E.I.; Wu, Y.; Guo, P.; Zhang, X.X.; Zhang, Y.Y.Y.Y.Y.; Xie, S.; Deng, J.J.; Bai, B.; Jin, H.; Zhu, S.; Wu, P.; Fan, C.; Sun, J.; Leal Filho, W.; Saari, U.; Fedoruk, M.; Iital, A.; Moora, H.; Klöga, M.; Voronova, V.; Lv, X.; Dong, Q.; Zuo, Z.; Liu, Y.Y.; Huang, X.; Wu, W.M.; Giordano, L.; Portacci, G.; Caroppo, C.; Di, M.; Liu, X.X.; Wang, W.; Wang, J.J.J.; Evans, A.E.; Mateo-Sagasta, J.; Qadir, M.; Boelee, E.; Ippolito, A.; Hossain, M.R.; Jiang, M.; Wei, Q.H.; Leff, L.G.; Mai, L.; Bao, L.J.; Shi, L.; Wong, C.S.; Zeng, E.Y.; Allen, S.; Allen, D.; Phoenix, V.R.; Le Roux, G.; Durántez Jiménez, P.; Simonneau, A.; Binet, S.; Galop, D.; Lee, H.; Kunz, A.; Shim, W.J.; Walther, B.A.; Hoellein, T.J.; Shogren, A.J.; Tank, J.L.; Risteca, P.; Kelly, J.J.; Trotter, B.; Ramsperger, A.F.R.M.; Raab, P.; Haberstroh, J.; Laforsch, C.; Tzoneva, M.; Forney, K.J.; Keel, P.K.; Walker, M.; Thornton, L.; De Choudhury, M.; Teevan, J.; Bulik, C.M.; Levinson, C.A.; Zerwas, S.; Halliwell, E.; Shen, C.; Wasylkiw, L.; Williamson, M.E.; Toumi, H.; Abidli, S.; Bejaoui, M.; Turner, S.; Horton, A.A.; Rose, N.L.; Hall, C.; Zhu, F.; Zhu, C.; Wang, C.; Gu, C.; Tiwari, M.; Rathod, T.D.; Ajmal, P.Y.; Bhangare, R.C.; Sahu, S.K.; Núñez, P.; García, A.; Mazarrasa, I.; Juanes, J.A.; Abascal, A.J.; Méndez, F.; Castanedo, S.; Medina, R.; Hardesty, B.D.; Polidoro, B.; Compa, M.; Shim, W.J.; Widianarko, B.; Wilcox, C.; Cordova, M.R.; Purwiyanto, A.I.S.; Suteja, Y.; Mohsen, M.; Wang, Q.; Zhang, L.; Sun, L.; Lin, C.; Yang, H.H.; Bauer-Civiello, A.; Critchell, K.; Hoogenboom, M.; Hamann, M.; Farady, S.E.; Ding, L.; Mao, R. fan, Guo, X.; Yang, X.; Zhang, Q.; Yang, C.; Zhang, S.; Wang, J.J.J.; Liu, X.X.; Qu, F.; Wang, X.X.X.X.; Wang, X.X.X.X.; Li, Y.Y.; Sun, Y.; Koelmans, A.A.; Mohamed Nor, N.H.; Hermsen, E.; Kooi, M.; Mintenig, S.M.; De France, J.; Li, Y.Y.; Wang, X.X.X.X.; Fu, W.; Xia, X.; Liu, C.C.; Min, J.; Zhang, W.; Crittenden, J.C.; Eo, S.; Hong, S.H.; Song, Y.K.; Han, G.M.; Shim, W.J.; Zhao, S.; Wang, T.; Zhu, L.; Xu, P.; Wang, X.X.X.X.; Gao, L.; Li, D.; Enfrin, M.; Dumée, L.F.; Lee, J.; Bordós, G.; Urbányi, B.; Micsinai, A.; Kriszt, B.; Palotai, Z.; Szabó, I.; Hantosi, Z.; Szoboszlay, S.; Rezaei, M.; Riksen, M.J.P.M.; Sirjani, E.; Sameni, A.; Geissen, V.; Malizia, A.; Monmany-Garzia, A.C.; Liu, F.; Olesen, K.B.; Borregaard, A.R.; Vollertsen, J.; Borges Ramirez, M.M.; Dzul Caamal, R.; Rendón von Osten, J.; van Wijnen, J.; Ragas, A.M.J.; Kroeze, C.; Liu, K.; Wang, X.X.X.X.; Fang, T.; Xu, P.; Zhu, L.; Li, D.; Chen, H.; Wang, S.S.; Guo, H.; Lin, H.; Zhang, Y.Y.Y.Y.Y.; Long, Z.; Huang, H.; Yuan, W.; Liu, X.X.; Wang, W.; Di, M.; Wang, J.J.J.; Kim, S.W.; An, Y.J.; Liu, C.C.; Li, J.; Zhang, Y.Y.Y.Y.Y.; Wang, L.; Deng, J.J.; Gao, Y.; Yu, L.; Zhang, J.; Sun, H.; Rocha-Santos, T.; Duarte, A.C.; Wang, W.; Wang, J.J.J.; Renner, G.; Nellessen, A.; Schwiers, A.; Wenzel, M.; Schmidt, T.C.; Schram, J.; Rios Mendoza, L.M.; Balcer, M.; Prata, J.C.; da Costa, J.P.J.P.; Duarte, A.C.; Rocha-Santos, T., Tan, X.; Yu, X.; Cai, L.; Wang, J.J.J.; Peng, J.; David, J.; Weissmannová, H.D.; Steinmetz, Z.; Kabelíková, L.; Demyan, M.S.; Šimečková, J.; Tokarski, D.; Siewert, C.; Schaumann, G.E.; Kučerík, J.;

Zhang, F.; Wang, Z.; Wang, S.S.; Fang, H.; Wang, D.; Asamoah, B.O.; Kanyathare, B.; Roussey, M.; Peiponen, K.E.; Unice, K.M.; Weeber, M.P.; Abramson, M.M.; Reid, R.C.D.; van Gils, J.A.G.; Markus, A.A.; Vethaak, A.D.; Panko, J.M.; Pivokonsky, M.; Cermakova, L.; Novotna, K.; Peer, P.; Cajthaml, T.; Janda, V.; Mintenig, S.M.; Löder, M.G.J.; Primpke, S.; Gerdts, G.; Barletta, M.; Lima, A.R.A.; Costa, M.F.; Shruti, V.C.; Jonathan, M.P.; Rodriguez-Espinosa, P.F.; Rodríguez-González, F.; Hu, D.; Shen, M.; Zhang, Y.Y.Y.Y.Y.; Zeng, G.; Rodrigues, S.M.; Almeida, C.M.R.; Silva, D.; Cunha, J.; Antunes, C.; Freitas, V.; Ramos, S.; Hüffer, T.; Metzelder, F.; Sigmund, G.; Slawek, S.; Schmidt, T.C.; Hofmann, T.; Xiong, X.; Wu, C.; Elser, J.J.; Mei, Z.; Hao, Y.; Rose, D.; Webber, M.; Watkins, L.; McGrattan, S.; Sullivan, P.J. and Walter, M.T. (2019). Study of marine debris around a tourist city in East China: Implication for waste management. Sci. Total Environ., 161, 834–840.

Fauziah, S.H.; Rizman-Idid, M.; Cheah, W.; Loh, K.H.; Sharma, S.; Noor, N.M.; Bordt, M.; Praphotjanaporn, T.; Samah, A.A.; Sabaruddin, J.S. and bin, George, M. (2021). Marine debris in Malaysia: A review on the pollution intensity and mitigating measures. Mar. Pollut. Bull.

Gelcich, S.; Buckley, P.; Pinnegar, J.K.; Chilvers, J.; Lorenzoni, I.; Terry, G.; Guerrero, M.; Castilla, J.C.; Valdebenito, A. and Duarte, C.M. (2014). Public awareness, concerns, and priorities about anthropogenic impacts on marine environments. Proc. Natl. Acad. Sci., U. S. A. 111, 15042–15047.

Hardesty, B.D.; Lawson, T.J.; van der Velde, T.; Lansdell, M. and Wilcox, C. (2017). Estimating quantities and sources of marine debris at a continental scale. Front. Ecol. Environ., 15, 18–25.

Harrigan, S.; Zsoter, E.; Alfieri, L.; Prudhomme, C.; Salamon, P.; Wetterhall, F.; Barnard, C.; Cloke, H. and Pappenberger, F. (2020). GloFAS-ERA5 operational global river discharge reanalysis 1979-present. Earth Syst. Sci., Data, 12, 2043–2060.

Hayati, Y.; Adrianto, L.; Krisanti, M.; Pranowo, W.S. and Kurniawan, F. (2020). Magnitudes and tourist perception of marine debris on small tourism island: Assessment of Tidung Island, Jakarta, Indonesia. Mar. Pollut. Bull., 158.

Hersbach, H.; Bell, B.; Berrisford, P.; Hirahara, S.; Horányi, A.; Muñoz-Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Schepers, D.; Simmons, A.; Soci, C.; Abdalla, S.; Abellan, X.; Balsamo, G.; Bechtold, P.; Biavati, G.; Bidlot, J.; Bonavita, M.; De Chiara, G.; Dahlgren, P.; Dee, D.; Diamantakis, M.; Dragani, R.; Flemming, J.; Forbes, R.; Fuentes, M.; Geer, A.; Haimberger, L.; Healy, S.; Hogan, R.J.; Hólm, E.; Janisková, M.; Keeley, S.; Laloyaux, P.; Lopez, P.; Lupu, C.; Radnoti, G.; de Rosnay, P.; Rozum, I.; Vamborg, F.; Villaume, S. and Thépaut, J.N. (2020). The ERA5 global reanalysis. Q. J. R.

Meteorol. Soc., 146, 1999–2049.

Horpet, P.-; Jaroensutasinee, M.- and Jaroensutasinee, K.-, (2021). Impacts of Tourism on Marine Debris and Microplastic Detection at Samui Island, Southern Thailand.

Hu, C. (2021). Remote detection of marine debris using satellite observations in the visible and near infrared spectral range: Challenges and potentials. Remote Sens. Environ., 259.

Iskandar, M.R.; Cordova, M.R. and Park, Y.G. (2022). Pathways and destinations of floating marine plastic debris from 10 major rivers in Java and Bali, Indonesia: A Lagrangian particle tracking perspective. Mar. Pollut. Bull., 185.

Iskandar, M.R.; Surinati, D.; Cordova, M.R. and Siong, K. (2021). Pathways of floating marine debris in Jakarta Bay, Indonesia. Mar. Pollut. Bull., 169.

Jambeck, J.R.; Geyer, R.; Wilcox, C.; Siegler, T.R.; Perryman, M.; Andrady, A.; Narayan, R. and Law, K.L. (2015). Plastic waste inputs from land into the ocean. Science, (80-.). 347, 768–771.

Jang, Y.C.; Hong, S.; Lee, J.; Lee, M.J. and Shim, W.J. (2014). Estimation of lost tourism revenue in Geoje Island from the 2011 marine debris pollution event in South Korea. Mar. Pollut. Bull., 81, 49–54.

Kisnarti, E.A.; Ningsih, N.S.; Putri, M.R.; Hendiarti, N. and Mayer, B. (2024). Dispersion of surface floating plastic marine debris from Indonesian waters using hydrodynamic and trajectory models. Mar. Pollut. Bull., 198.

Kok, P.H.; Wijeratne, S.; Akhir, M.F.; Pattiaratchi, C.; Roseli, N.H. and Ali, F.S.M. (2021). Interconnection between the southern south china sea and the java sea through the karimata strait. J. Mar. Sci. Eng., 9.

Kubota, M. (1994). A mechanism for the accumulation of floating marine debris north of Hawaii. J. Phys. Oceanogr., 24, 1059–1064.

Kuncoro, I.; Zamani, N.P.; Subhan, B. and Cahyani, N.K.D. (2023). eDNA assessment of scleractinian diversity and distribution in Lemukutan Island, Indonesia. Biodiversitas, 24, 4185–4191.

Kushadiwijayanto, A.A.; Apriansyah. and Idiawati, N. (2017). Pemodelan Arus Musiman di Perairan Lemukutan Kalimantan Barat. Pros. SEMIRATA 2017 Bid. MIPA BKS-PTN 1034–1040.

Lebreton, L.C.M.; Greer, S.D. and Borrero, J.C. (2012). Numerical modelling of floating debris in the world's oceans. Mar. Pollut. Bull., 64, 653–661.

Lebreton, L.C.M.; Van Der Zwet, J.; Damsteeg, J.W.; Slat, B.; Andrady, A. and

Reisser, J. (2017). River plastic emissions to the world's oceans. Nat. Commun. 8.

Lett, C.; Verley, P.; Mullon, C.; Parada, C.; Brochier, T.; Penven, P. and Blanke, B. (2008). A Lagrangian tool for modelling ichthyoplankton dynamics. Environ. Model. Softw. 23, 1210–1214.

Lippiatt, S.; Opfer, S. and Arthur, C. (2013). Marine Debris Monitoring and Assessment. NOAA Technical Memorandum NOS-OR&R-46, NOAA Technical Memorandum NOS-OR&R-46.

Liu, K.; Wu, T.; Wang, X.; Song, Z.; Zong, C.; Wei, N. and Li, D. (2019). Consistent Transport of Terrestrial Microplastics to the Ocean through Atmosphere. Environ. Sci. Technol., 53, 10612–10619.

Lorenzi, L.; Reginato, B.C.; Mayer, D.G. and Dantas, D.V. (2020). Plastic floating debris along a summer-winter estuarine environmental gradient in a coastal lagoon: how does plastic debris arrive in a conservation unit? Environ. Sci. Pollut. Res., 27, 8797–8806.

Macias, D.; Cózar, A.; Garcia-Gorriz, E.; González-Fernández, D. and Stips, A. (2019). Surface water circulation develops seasonally changing patterns of floating litter accumulation in the Mediterranean Sea. A modelling approach. Mar. Pollut. Bull., 149.

Martinez, E.; Maamaatuaiahutapu, K. and Taillandier, V. (2009). Floating marine debris surface drift: Convergence and accumulation toward the South Pacific subtropical gyre. Mar. Pollut. Bull., 58, 1347–1355.

Martínez-Vicente, V.; Clark, J.R.; Corradi, P.; Aliani, S.; Arias, M.; Bochow, M.; Bonnery, G.; Cole, M.; Cózar, A.; Donnelly, R.; Echevarría, F.; Galgani, F.; Garaba, S.P.; Goddijn-Murphy, L.; Lebreton, L.; Leslie, H.A.; Lindeque, P.K.; Maximenko, N.; Martin-Lauzer, F.R.; Moller, D.; Murphy, P.; Palombi, L.; Raimondi, V.; Reisser, J.; Romero, L.; Simis, S.G.H.; Sterckx, S.; Thompson, R.C.; Topouzelis, K.N.; van Sebille, E.; Veiga, J.M. and Vethaak, A.D. (2019). Measuring marine plastic debris from space: Initial assessment of observation requirements. Remote Sens., 11.

Matthews, J.P.; Ostrovsky, L.; Yoshikawa, Y.; Komori, S. and Tamura, H. (2017). Dynamics and early post-tsunami evolution of floating marine debris near Fukushima Daiichi. Nat. Geosci., 10, 598–603.

Mghili, B.; Analla, M.; Aksissou, M. and Aissa, C. (2020). Marine debris in Moroccan Mediterranean beaches: An assessment of their abundance, composition and sources. Mar. Pollut. Bull., 160.

Miladinova, S.; Macias, D.; Stips, A. and Garcia-Gorriz, E. (2020). Identifying distribution and accumulation patterns of floating marine debris in the Black Sea. Mar. Pollut. Bull., 153.

Mogollón, R.; Pietri, A.; Tam, J. and Colas, F. (2023). Comprehensive characterization of Marine Heatwaves in a coastal Northern Humboldt Current System regional model over recent decades. Ocean Model. 186.

Mugilarasan, M.; Karthik, R.; Purvaja, R.; Robin, R.S.; Subbareddy, B.; Hariharan, G.; Rohan, S.; Jinoj, T.P.S.; Anandavelu, I.; Pugalenthi, P. and Ramesh, R. (2021). Spatiotemporal variations in anthropogenic marine litter pollution along the northeast beaches of India. Environ. Pollut., 280.

Noor, S. Y.; Riani, E.; Hariyadi, S.; Butet, N. A. and Cordova, M. R. (2025). Abundance and Characteristics of Microplastics in Surface Waters of Banten Bay, Serang, Indonesia. Egyptian Journal of Aquatic Biology & Fisheries, 29(3): 61–79.

Paler, M.K.O.; Malenab, M.C.T.; Maralit, J.R. and Nacorda, H.M. (2019). Plastic waste occurrence on a beach off southwestern Luzon, Philippines. Mar. Pollut. Bull., 141, 416–419.

Penven, P.; Cambon, G.; Marchesiello, P.; Sepulveda, A.; Benshila, R.; Illig, S.; Jullien, S.; Corre, M. Le, Gentil, S. Le. and Morvan, G. (2022). CROCO tools.

Pereiro, D.; Souto, C. and Gago, J. (2019). Dynamics of floating marine debris in the northern Iberian waters: A model approach. J. Sea Res. 144, 57–66.

PlasticsEurope. (2020). Plastics − the Facts 2020. Brussels, PlasticEurope.

Provencher, J.F.; Liboiron, M.; Borrelle, S.B.; Bond, A.L.; Rochman, C.; Lavers, J.L.; Avery-Gomm, S.; Yamashita, R.; Ryan, P.G.; Lusher, A.L.; Hammer, S.; Bradshaw, H.; Khan, J. and Mallory, M.L. (2020). A Horizon Scan of research priorities to inform policies aimed at reducing the harm of plastic pollution to biota. Sci. Total Environ., 733.

Purba, N.P.; Handyman, D.I.W.; Pribadi, T.D.; Syakti, A.D.; Pranowo, W.S.; Harvey, A. and Ihsan, Y.N. (2019). Marine debris in Indonesia: A review of research and status. Mar. Pollut. Bull.

Purwiyanto, A.I.S.; Prartono, T.; Riani, E.; Naulita, Y.; Cordova, M.R. and Koropitan, A.F. (2022). The deposition of atmospheric microplastics in Jakarta-Indonesia: The coastal urban area. Mar. Pollut. Bull., 174.

Purnama, D.; Zamani, N. P.; Bengen, D. G. and Cordova, M. R. (2025). Study on Plastic Ingestion in Carcasses Sea Turtles on Enggano Island, Indonesia. Egyptian Journal of Aquatic Biology & Fisheries, 29(1): 27–53.

Rudianto, A.; Dewi, Y.S.K. and Burhanuddin, B. (2020). Ecotourism Development of

Snorkeling and Diving Activity toward Coral Reef Habitats in the Lemukutan Islands of Bengkayang Regency. AQUASAINS 8, 795.

Sadiq, D. M. A. and Al-Hejuje, M. M. (2025). Evaluation of Microplastic Pollution in Water of Shatt Al-Arab River, Southern of Iraq. Egyptian Journal of Aquatic Biology & Fisheries, 29(3): 1349–1361.

Shchepetkin, A.F. and McWilliams, J.C. (2005). The regional oceanic modeling system (ROMS): A split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Model, 9, 347–404.

Suryono, D.D.; Ati, R.N.A.; Setiawan, A.; Syakti, A.D.; Rustam, A.; Salim, H.L.; Sudirman, N.; Daulat, A.; Astrid K, M.; Prasetiawan, N.R.; Pranowo, W.S. and Jayawiguna, M.H. (2021). Distribution of macro plastic debris in Muaragembong coastal bay during the east moonson and the east to west monsoon transition in 2020, in: E3S Web of Conferences.

Suteja, Y.; Atmadipoera, A.S.; Riani, E.; Nurjaya, I.W.; Nugroho, D. and Cordova, M.R. (2021a). Spatial and temporal distribution of microplastic in surface water of tropical estuary: Case study in Benoa Bay, Bali, Indonesia. Mar. Pollut. Bull., 163.

Suteja, Y.; Atmadipoera, A.S.; Riani, E.; Nurjaya, I.W.; Nugroho, D. and Purwiyanto, A.I.S. (2021b). Stranded marine debris on the touristic beaches in the south of Bali Island, Indonesia: The spatiotemporal abundance and characteristic. Mar. Pollut. Bull., 173.

Tahir, A.; Werorilangi, S.; Isman, F.M.; Zulkarnaen, A.; Massinai, A. and Faizal, A. (2019). Short-Tem Observation on Marine Debris at Coastal Areas of Takalar District and Makassar City, South Sulawesi, Indonesia. J. Ilmu Kelaut., SPERMONDE 4.

Terzi, Y. and Seyhan, K. (2017). Seasonal and spatial variations of marine litter on the south-eastern Black Sea coast. Mar. Pollut. Bull., 120, 154–158.

Tramoy, R.; Gasperi, J.; Colasse, L.; Noûs, C. and Tassin, B. (2021). Transfer dynamics of macroplastics in estuaries – New insights from the Seine estuary: Part 3. What fate for macroplastics? Mar. Pollut. Bull., 169.

van Emmerik, T.; van Klaveren, J.; Meijer, L.J.J.; Krooshof, J.W.; Palmos, D.A.A. and Tanchuling, M.A. (2020). Manila River Mouths Act as Temporary Sinks for Macroplastic Pollution. Front. Mar. Sci., 7.

Van Sebille, E.; Aliani, S.; Law, K.L.; Maximenko, N.; Alsina, J.M.; Bagaev, A.; Bergmann, M.; Chapron, B.; Chubarenko, I.; Cózar, A.; Delandmeter, P.; Egger, M.; Fox-Kemper, B.; Garaba, S.P.; Goddijn-Murphy, L.; Hardesty, B.D.; Hoffman, M.J.; Isobe, A.; Jongedijk, C.E.; Kaandorp, M.L.A.;

Khatmullina, L.; Koelmans, A.A.; Kukulka, T.; Laufkötter, C.; Lebreton, L.; Lobelle, D.; Maes, C.; Martinez-Vicente, V.; Morales Maqueda, M.A.; Poulain-Zarcos, M.; Rodríguez, E.; Ryan, P.G.; Shanks, A.L.; Shim, W.J.; Suaria, G.; Thiel, M.; Van Den Bremer, T.S. and Wichmann, D. (2020). The physical oceanography of the transport of floating marine debris. Environ. Res. Lett.

Vlachogianni, T.; Fortibuoni, T.; Ronchi, F.; Zeri, C.; Mazziotti, C.; Tutman, P.; Varezić, D.B.; Palatinus, A.; Trdan, Š.; Peterlin, M.; Mandić, M.; Markovic, O.; Prvan, M.; Kaberi, H.; Prevenios, M.; Kolitari, J.; Kroqi, G.; Fusco, M.; Kalampokis, E. and Scoullos, M. (2018). Marine litter on the beaches of the Adriatic and Ionian Seas: An assessment of their abundance, composition and sources. Mar. Pollut. Bull., 131, 745–756.

Weatherall, P.; Marks, K.M.; Jakobsson, M.; Schmitt, T.; Tani, S.; Arndt, J.E.; Rovere, M.; Chayes, D.; Ferrini, V. and Wigley, R. (2015). A new digital bathymetric model of the world’s oceans. Earth Sp. Sci., 2, 331–345.

Wilson, S.P. and Verlis, K.M. (2017). The ugly face of tourism: Marine debris pollution linked to visitation in the southern Great Barrier Reef, Australia. Mar. Pollut. Bull., 117, 239–246.

Zhang, K. (2021). Global plastics industry - statistics & facts. Statista.

Zhao, S.; Zhu, L. and Li, D. (2015). Characterization of small plastic debris on tourism beaches around the South China Sea. Reg. Stud. Mar. Sci. 1, 55–62.