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Holes on surfaces of the weathered plastic fragments from coastal beaches

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ABSTRACT

The surface morphology of weathered plastics undergoes a variety of changes. In this study, 3950 plastic fragments from 26 beaches around the world, were assessed to identify holes. Holes were identified on 123 fragments on 20 beaches, with the highest frequency (10.3 %) being identified at Qesm AL Gomrok Beach in Egypt. The distribution of holes could be divided into even, single-sided, and random types. The external and internal holes were similar in size (37 ± 15 μm) of even type fragments. The external holes were larger than the internal holes in single-sided (516 ± 259 μm and 383 ± 161 μm) and random (588 ± 262 μm and 454 ± 210 μm) fragment types. The external hole sizes were positively correlated with the internal hole sizes for each type. This study reports a novel deformation phenomenon on the surface of weathered plastics and highlights their potential effects on plastics.

1. Introduction

Plastic, one of the greatest inventions of the last century, is widely used in daily activities (Rabesandratana, 2021). It is estimated that approximately 90 % of used plastics have been discarded into the environment (Najafi, 2013). Plastic litter reaches aquatic systems through wind, rivers, tides, animals, and oceanic currents (Welden and Lusher, 2017; Zheng et al., 2019). Beaches and coastal areas are one of the accumulation areas for plastic marine litter (Serra-Gonçalves et al., 2019). Plastics stranded on beaches undergo continuous fragmentation and degradation processes due to physical, chemical, and biological factors (Arp et al., 2021; Horne et al., 2020; Long et al., 2017; Qiu et al., 2022). Consequently, the larger plastics fragment into smaller items and reach microscopic size, where they are known as microplastics (<5 mm) (Thompson et al., 2004).

Differences in the polymer type and external factors can influence the degree of fragmentation, from slight surface deformation to complete breakdown (Liu et al., 2022). Changes in surface characteristics result from weathering processes and deterioration degrees under natural (e.g., U.V. radiation and mechanical abrasion) and artificial conditions (e.g., laboratory degradation studies) (Halle et al., 2016). Previous studies have reported specific features occurring in plastic surfaces, such as yellowing, delamination, pits, and cracks (Deng et al., 2022; Halle et al., 2017; Liu et al., 2019). These surface features and morphological characteristics are also commonly found in field samples from beaches and coastal areas (Edo et al., 2019; Zhou et al., 2018). Most studies only document visually the morphological features, roughly demonstrating and describing the general changes of weathering and fragmentation of plastics (Monte et al., 2022; Wu et al., 2021).

The aging and degradation processes of plastics are complex and cause various morphological changes. In material science, holes can be viewed as a consequence of fragmentation, driving further surface failures of products (Li et al., 2021). They have been widely documented in materials (Table S1) such as functionally gradient brittle materials (Li et al., 2021), metallic glass (Sarac and Schroers, 2013), ductile metals (Dávila et al., 2005), and co-emulsion paint (Cogulet et al., 2018). Since

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plastics are likely to weather under environmental conditions, we hypothesized that holes would occur on the plastic surface during weathering, similarly to other materials.

Therefore, a large-scale field investigation of plastic fragments from 26 beaches in 8 countries around the world was conducted to assess and classify the distribution patterns of holes on plastics, according to their characteristics and origin. Our aim was to determine the occurrence and features of holes on surfaces of weathered plastics in coastal environments. To our best knowledge, this is the first research about the characteristics and effects of holes on weathered plastic.

2. Materials and methods

2.1. Study area

Sampling was conducted on 26 coastal beaches, in 8 countries between 2020 and 2022 (Fig. 1; Table S2). A harmonized sampling protocol was provided to all participants. Only coastal beaches were chosen as research areas, with sampling occurring within a 5000 m^2 area. Researchers targeted accumulation areas to ensure enough plastic fragments would be collected. GPS coordinates were recorded at each site.

2.2. Sampling design and data collection

All plastic samples were collected along the coastline following guidelines provided by the research team. Volunteers wore latex gloves and used a stainless-steel tweezer to carefully pick up visible plastic fragments. At least 150 plastics (0.1–25 cm) were randomly collected from each site. All plastic fragments in each beach were kept in one aluminum foil bag prior to further analysis. Researchers photographed plastic fragments using cell phones or a light microscope in their respective laboratories. The photos allow the research team to confirm whether sizes and shapes were suitable. When samples did not match the requirements, further collection was required. Samples were then posted to our facilities in Shanghai, following all the national and international requirements.

2.3. Selection and cleaning of plastics in the laboratory

Once in the laboratory, all plastic fragments were measured using a vernier caliper (precision of 0.1 cm; JZYQ-001, Information Technology Company, China). A total of 3950 plastic fragments, ranging between 0.5 and 5.0 cm, were selected as samples for further analysis (Table S2). Each fragment was photographed using a digital camera (FDR-AX60, Sony, Japan) at a unified focal distance. In plastics that were contaminated with soil or covered with mud, a soft brush was used for cleaning them, while avoiding causing any additional damage. Plastic fragments with organisms attached to the surface were not subjected to the cleaning process. All plastics were then observed under a stereomicroscope (SMZ140-N2LED, Motic, China) to determine whether holes were present on the surfaces. Each fragment was stored in a sealed bag adequately labeled with a specific code.

2.4. Optical microscopic inspection of holes

For the examination of the internal characters, plastics with different characteristics of external holes were dissected crossly using a stainless-steel razor blade. The details of holes on the plastic surfaces and cross-sections were observed and photographed using a Carl Zeiss Discovery V8 Stereomicroscope (Micro Imaging GmbH, Göttingen, Germany). The stereomicroscope was equipped with a 9.0-million-pixel AxioCam Icc3 camera. During image capturing, plastics were placed on a microscope carrier with black flannelette. The magnifications were set from 10× to 80×. The image synthesis system of CapStudio software (Image Technology Company, China) was used to obtain a high-definition image for the analysis of the hole morphology. The area, color, and shape of plastics, as well as the number and diameter of holes, were calculated and recorded using ImageJ software (Fiji, version 1.53c).

2.5. Identification of polymer composition

The polymer composition of all plastics was determined using a Fourier Transform Infrared spectrometer (FTIR; Nicolet iS5N, Thermo Scientific, U.S.A.). The samples were measured under transmission mode with 8 s scan times. The spectra were acquired from a spectral resolution of 8 cm^{-1} and a spatial resolution of 6.25 μm. The spectral

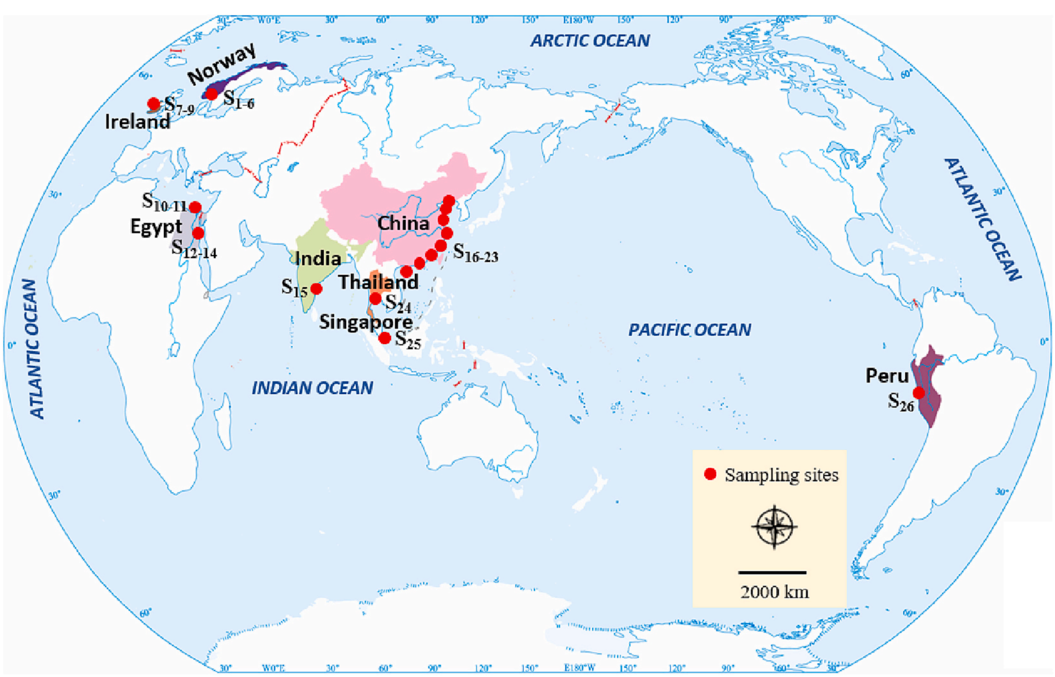

Fig. 1. Sampling sites for plastic fragments from 26 beaches in 8 countries.

range was set from 4000 to 600 cm^{-1}. All spectra were compared with the in-built library from Thermo Fisher to identify the polymer type. Spectral matches above 70 % were accepted as plastics, and the locations of specific peaks were checked manually.

2.6. Data analysis

The results were presented as mean ± standard deviation (SD). Statistical analysis was performed using Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA, U.S.A.) and SPSS Statistics 22.0 (IBM Corp, Armonk, NY, U.S.A.). The homogeneity of variance was assessed using Levene's test. The normality of the data was first tested with the Shapiro–Wilk test. Non-parametric tests were used when the data was not normally distributed. Mann–Whitney *U* test was used to analyze the differences between the two groups, and the differences among multiple groups were accessed with the Kruskal–Wallis test, followed by multiple comparisons. Spearman's rank correlation and regression analysis were used to analyze the correlation of size between the internal and external holes. The significant level was established at $p < 0.05$ and $p < 0.01$.

3. Results and discussion

3.1. Occurrence of holes on the surface of plastic fragments

The properties of each plastic fragment were carefully measured and analyzed. The dominant composition of plastics was polypropylene (PP, 50 %) and polyethylene (PE, 45 %). Both polymers were commonly found in each country and at each site (Table S2). Plastic fragments ranged in size from 0.5 to 4.9 cm in length, predominantly in 1–2 cm fraction (60 %). The size fraction of plastics collected from different countries was similar (Fig. S1A; $p < 0.01$, Kruskal–Wallis test). The most common type was quadrilateral (50 %), followed by pentagon (19 %) and irregular polygons (sides > 6, 13 %) (Fig. S1B). In addition, triangular plastics were also more frequent in Egypt (19 %; $p < 0.01$, Kruskal–Wallis test). Blue was the predominant color (30 %), followed by white (27 %). In comparison to other sites, there were more transparent plastics in the Irish samples (39 %) (Fig. S1C; $p < 0.01$, Kruskal–Wallis test).

The surface morphology of plastics showed high variations due to the different degrees of weathering. In addition to the common weathered appearance, some obvious holes were also found on the surface of plastics. Some plastic fragments were evenly covered with small holes on each side with obvious fillers (Fig. 2A, B). There were also some plastic fragments with holes only on one surface (Fig. 2C, D), and divergent deformation (e.g., crack) was observed on the opposite surface of the same fragment (Fig. 2E, F). Holes might also appear only on the blistered areas of the plastic surface (Fig. 2G, H). In addition, the holes were randomly distributed on irregular polyhedral-shaped plastics (Fig. 2I, J). Generally, most of the holes were characterized as round with relatively smooth edges, with each hole having a circular cavity of a certain depth. The holes were clearly distinguished from the pits commonly found on aged plastics (Fig. 2K, L). Specifically, the pits were relatively shallow, and no visible edges or deep cavities were identified.

Holes were found on plastics in all countries sampled (Table 1). Specifically, plastics with holes existed in 20 out of 26 sampling beaches. A total of 123 fragments with holes were found, accounting for 3.1 % of all samples. The percentage of plastic with holes was 1.1 %–5.2 % in terms of country and 0.7 %–10.3 % in terms of site. The highest frequency of holes (10.3 %) was at Qesm AL Gomrok Beach (S_{10}) in Egypt. The lowest was 0.7 % at both Tjuvholmen Bystrand Beach (S_6) in Norway and National Institute of Oceanography and Fisheries (NIOF) Beach (S_{12}) in Egypt. The number of holes on plastic surfaces varied from 2 to 226 holes/cm^2, and the diameter ranged from 16 to 1120 μm. The highest density (103 ± 87 holes/cm^2) and smallest size (218 ± 390 μm)

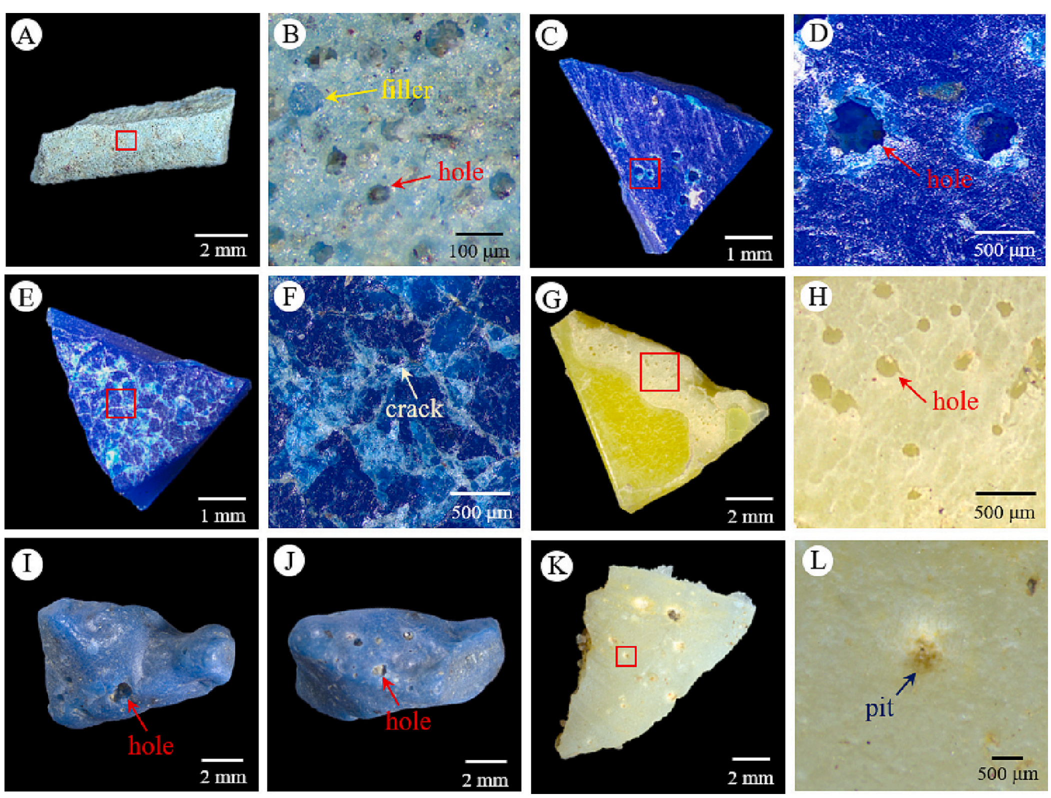

Fig. 2. Morphological surface characteristics of small plastic fragments collected from coastal beaches. Plastic covered with evenly distributed holes (A) and the embedded fillers in the holes (B). Plastic surface with holes (C) and the enlarged view of holes (D). Plastic surface with cracks (E) and the enlarged view of cracks (F). Blistered plastic surface (G) and holes on the blistered areas (H). Holes on irregularly shaped plastic (I, J). Surface morphology of aged plastic fragment (K) and pits on the plastic surface (L).

Table 1
Basic features of holes on plastic surface.

Site	Location	Number of plastic fragments	Number of plastics with holes	Frequency of plastics with holes (%)	Diameter of holes (μm)	Number of holes (holes/ cm^2)
Norway						
S_1	Paradisbukta Beach	345	18	5.2	268 ± 385	95 ± 51[a]
S_2	Ommen Beach	65	3	4.6	441 ± 483	13 ± 9
S_3	Fornebustranda Beach	48	2	4.2	597 ± 319	8 ± 1
S_4	Bygdøy Sjøbad Beach	268	16	6.0	218 ± 390	103 ± 87
S_5	Hvervenbukta Beach	213	4	1.9	418 ± 303	5 ± 3
S_6	Tjuvholmen Bystrand Beach	284	2	0.7	638 ± 496	3 ± 1
Ireland						
S_7	Dooey Beach	93	2	2.2	542 ± 321	9 ± 3
S_8	Magheroarty Beach	75	0	0	0	0
S_9	Gortnamullan Beach	20	0	0	0	0
Egypt						
S_{10}	Qesm Al Gomrok Beach	126	13	10.3	602 ± 189	3 ± 0
S_{11}	Ras AL Tin Beach	119	10	8.4	738 ± 229	5 ± 2
S_{12}	NIOF Beach[b]	137	1	0.7	583 ± 156	8 ± 1
S_{13}	Youth City Beach	156	3	1.9	649 ± 313	5 ± 4
S_{14}	Falfala Beach	149	9	6.0	594 ± 273	5 ± 2
India						
S_{15}	Puthupettai Beach	122	3	2.5	604 ± 524	9 ± 7
China						
S_{16}	Dalian Beach	108	0	0	0	0
S_{17}	Yantai Beach	96	0	0	0	0
S_{18}	Lianyungang Beach	103	0	0	0	0
S_{19}	Shanghai Beach	184	3	1.6	426 ± 318	3 ± 2
S_{20}	Taizhou Beach	106	0	0	0	0
S_{21}	Xiamen Beach	110	5	4.5	432 ± 233	6 ± 4
S_{22}	Zhuhai Beach	103	1	1.0	451 ± 262	4 ± 1
S_{23}	Haikou Beach	104	2	1.9	566 ± 335	4 ± 2
Thailand						
S_{24}	Luk Lom Beach	286	10	3.5	573 ± 209	4 ± 2
Singapore						
S_{25}	East Coast Park Beach	142	3	2.1	539 ± 524	6 ± 6
Peru						
S_{26}	Sombrillas Beach	388	13	3.4	484 ± 108	9 ± 2

[a] Mean ± standard deviation.
[b] National Institute of Oceanography and Fisheries (NIOF).

were found on plastic fragments collected from Bygdoy Sjobad Beach (S_4), Norway ($p < 0.01$, Kruskal–Wallis test).

Previous studies on plastics have only provided photographs of pits on the surface (Hu et al., 2023). Optical microscope images have been used to demonstrate the morphology of holes on surface coatings prepared from a co-emulsion of poly(butylacrylate/methyl methacrylate) (Cogulet et al., 2018). The description and classification of hole morphology lack research reports. Especially, the details of holes on the plastic surface were missing in natural environments. Compared to the images reported in previous studies, the holes identified in this study differed significantly from the pits in morphological characteristics (Sarkar et al., 2021; Yu et al., 2018). The primary difference between a hole and a pit was that the hole had a distinct edge and cavity. Therefore, the word ‘hole’ was chosen to name the defect found on the plastic fragments in this study. Since the hole found in this research was a relatively novel and unique deformation, it was necessary to explore its form and type in detail.

3.2. Internal structures of plastic fragments and their relation to the external holes

Internal morphological features were explored through the cross-section analysis and compared with the external holes. A total of 42 plastics were analyzed, accounting for 34 % of the plastics with holes. Some fragments were covered with small holes on all surfaces (Fig. 3A, B), and the internal holes were also evenly distributed in the cross-section of these plastics (Fig. 3C, D). Overall, these small external and internal holes were similar to each other in morphology. All of the edges of holes were more rounded, and the cavities were regular hemispheres. Some of the cavities were embedded with fillers. Some flat plastic fragments with external holes on one side usually had many different characteristics on the other side (Fig. 3E, F), and the internal holes tend to distribute near the surface of one side with external holes (Fig. 3G, H). Compared to the external hole, the edge and cavity of the internal hole were more rounded. For irregularly shaped plastics, the external holes were randomly and irregularly distributed on the surface (Fig. 3I, J), and internal holes with rounded edges and hemispheres cavity were also randomly distributed on the cross-section (Fig. 3K, L). The color

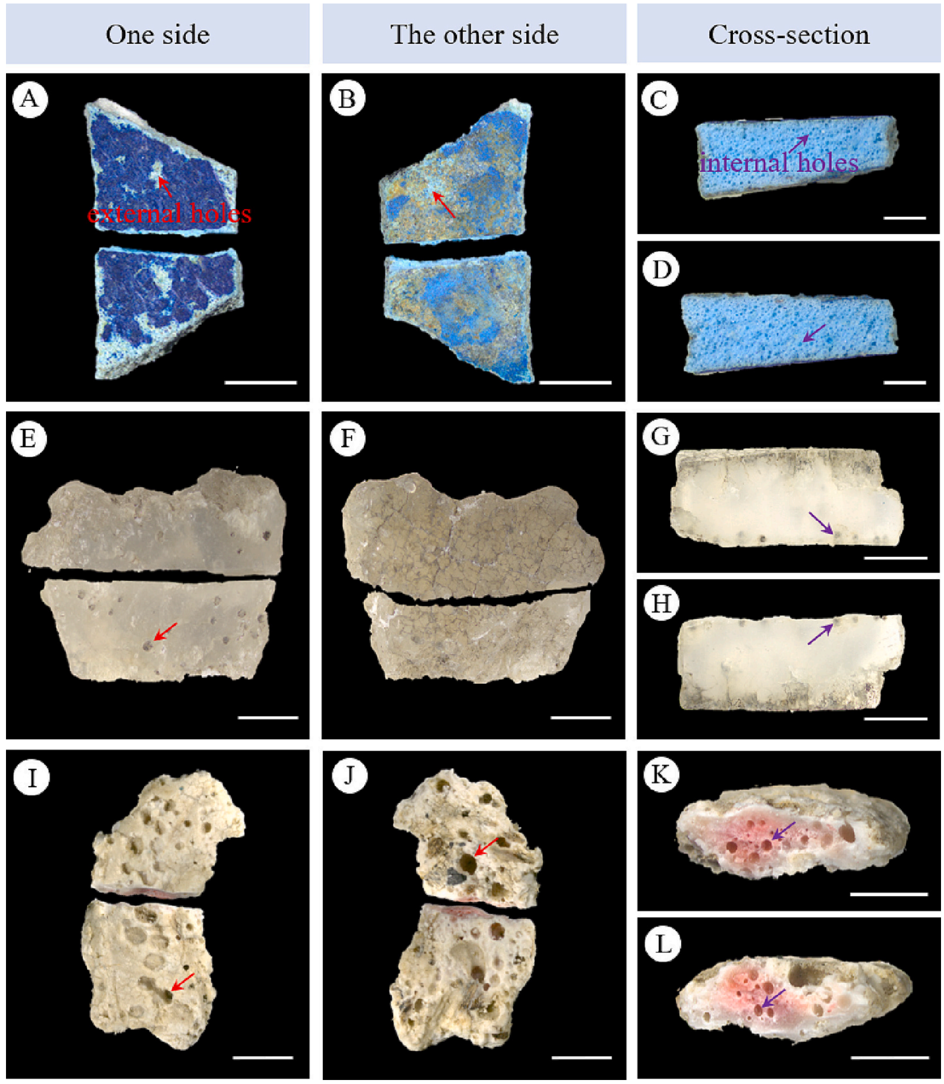

Fig. 3. Spatial distribution of holes on plastic surface and cross-sectionally. (A, B) Plastic fragments with evenly distributed holes on the surface. (C, D) Plastic cross-section with evenly distributed holes. (E, F) Plastics with different surface morphology. (G, H) Tendency arrangement of holes on the cross-section. (I, J) Irregular plastic with randomly distributed holes on the surface. (K, L) Randomly distributed holes on the cross-section. Scale bars = 1 cm.

gradually lightened from the center of the plastic to the periphery. Generally, the external holes were larger than the internal ones.

The sizes of the internal and external holes were statistically analyzed according to three different distribution types in this study (Fig. 4A). The internal hole size ranged from 15 μm to 58 μm (37 ± 15 μm) and the size range of the external hole was 16–60 μm (37 ± 15 μm) for evenly distributed holes ($p > 0.05$; Mann–Whitney *U* test). The internal and external holes evenly distributed were similar in size. The internal hole sizes were from 140 to 720 μm (383 ± 161 μm) and the external hole sizes were from 140 to 1020 μm (516 ± 259 μm) for single-side distributed holes ($p < 0.01$, Mann–Whitney U test). The size range of the internal hole size was 140–920 μm (454 ± 210 μm) and the size range of the external hole was 110–1120 μm (588 ± 262 μm) for randomly distributed holes ($p < 0.05$, Mann–Whitney U test). The external holes were significantly larger than the internal holes for single-sided and random distribution. In addition, there was a correlation between the size of internal and external holes of each type. The Spearman's rank correlation coefficient for the three types was 0.64, 0.60, and 0.63, respectively ($p < 0.01$). The regression analysis showed a significant positive effect of the internal hole size on the external hole size (Fig. 4B–D). The significance of each type was <0.001, ensuring the validity of the regression equation. The relationship between the numbers of holes was not analyzed because of the different spatial locations of the internal and external holes. The internal holes were located on the cross-section, while the external holes were located on the surface.

Holes appeared not only on the surface but also in the cross-section of plastics, thus inspiring us to explore the causes of their formation. According to previous studies, the even distribution of holes inside and outside the plastic is a deliberate process (Banerjee and Ray, 2020; Seo et al., 2011). The fillers in the cavities might be related to engineering needs for soft inclusions into the holes to create tensile and impact-resistant plastic materials (Zhang et al., 2013). For plastic fragments with a tendentious distribution of holes, materials science studies suggest that the internal holes are defects caused by the machining process (Li et al., 2021). As the surface layer continued to age and peel off, the holes were gradually exposed. The plastic in the air medium shows a higher number of holes on its surface compared to the brine medium (Feng et al., 2022; Ranjan and Goel, 2021). The holes on plastic surfaces continue to age and break down, resulting in an increase in diameter (Cogulet et al., 2018). Therefore, we considered the plastic surface with holes as the side exposed to air for a longer time period.

This study found that irregularly shaped plastics were distinctly different from manufactured plastic fragments in origin, appearance,

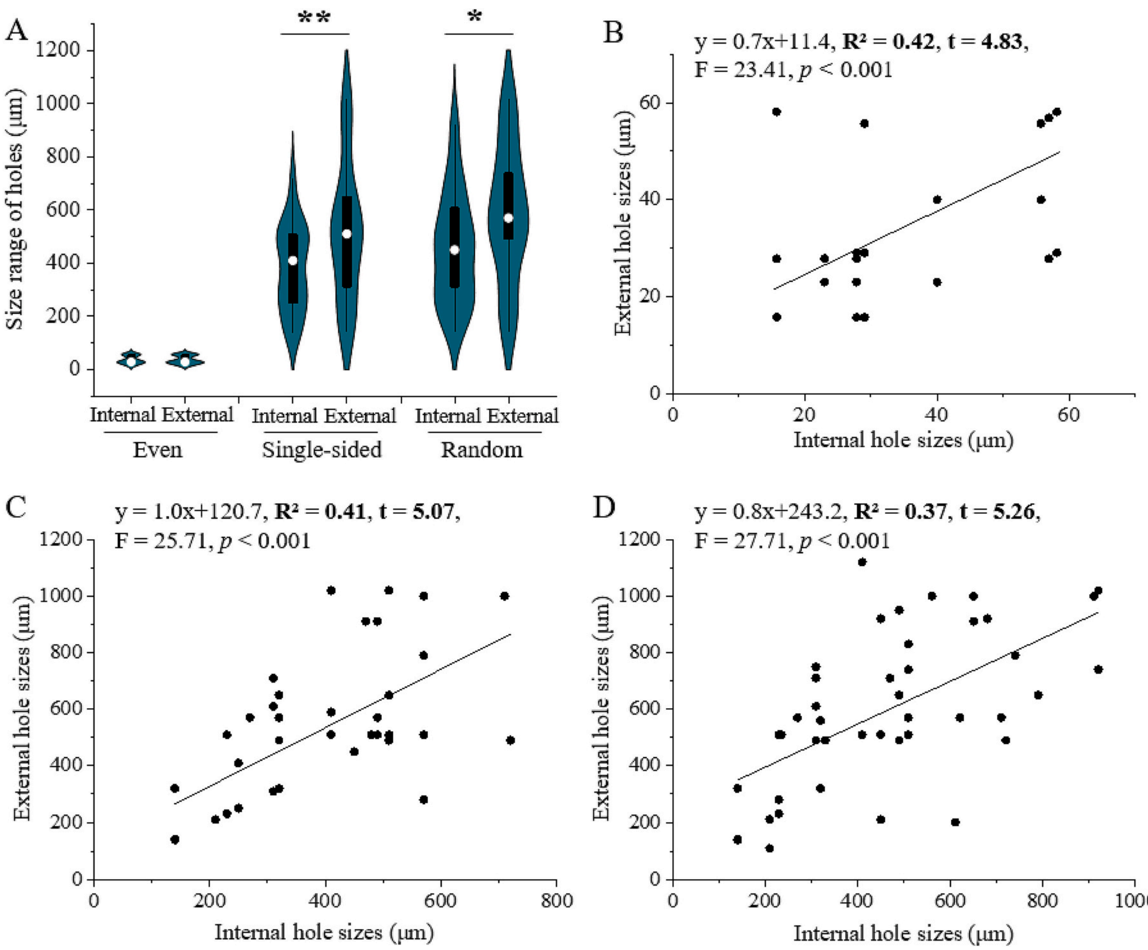

Fig. 4. (A) Size of internal holes and external holes as even, single-sided, and random distribution. The results were presented as mean ± SD. *: $p < 0.05$ and **: $p < 0.01$. Correlation of sizes between the internal hole and external hole of even distribution (B), single-sided distribution (C), and random distribution (D).

and thickness. Previous studies have reported that this type of plastic has been plasticized into pyroplastic, plasticrusts, and plastiglomerate by melting or burning plastics (De-la-Torre et al., 2021; Ellrich and Ehlers, 2022). When the plastic is heated, globules of air are formed and trapped in the once-melted plastic. Later, the globules of air are gradually exposed and ruptured into holes by external environmental effects (Corcoran and Jazvac, 2020). Information on the interactions between pyroplastic and environmental factors is still very scarce. Ultimately, internal holes were linked to material design, defects, or human influence (e.g., burning), while external holes were progressively exposed and enlarged due to the occurrence of internal holes and interaction with environmental factors.

This study defined the plastic with holes into three categories and presented them with visual patterns, according to the distribution characteristics and formation reasons of holes on the surface and cross-section (Fig. 5). Type A referred to the 'even distribution'. It meant that the external holes and the internal holes were evenly distributed on plastic fragments with similar shapes and sizes. Holes were deliberately machined structures and some holes were embedded with fillers (Fig. 5A). Type B referred to the 'single-sided distribution'. It meant that the external holes were distributed on one surface of the plastic fragment, and the internal holes were arranged close to the surface with holes indicating that there may be an inevitability in the location of the holes (Fig. 5B). Type C referred to the 'random distribution'. It meant that the external and the internal holes were randomly distributed on the irregularly shaped plastic surface and inside (Fig. 5C).

3.3. Dynamic changes of holes in plastic fragments

We found that the occurrence of holes on the plastic surface caused other changes around or inside the cavity of the holes. Several holes were connected by cracks on the surface of plastics (Fig. 6A). Magnification revealed multiple cracks extending outward from the edge of holes (Fig. 6B). The plastics were usually contaminated with sediments (Fig. 6C). Coarse sands with various grain sizes were trapped in holes on the surface (Fig. 6D). In addition, more colonization did not pass through the surface, but specifically through holes (Fig. 6E). The remains of host organism were found inside in holes (Fig. 6F). Inevitably, the filler embedded in the hole was also exposed (Fig. 6G). For example, the filler found in this hole was rounded and spherical in shape with a diameter of only 248 μm (Fig. 6H).

The holes on the surface have an important role in the fragmentation and degradation of plastics. The holes on the plastic surface induced irregular cracks. Cracks lay the foundation for plastic fragmentation (Deng et al., 2022). This phenomenon was clearly verified in the field of stainless steel materials (Cao et al., 2019; Xiang et al., 2018). Sands and gravels of different grain sizes were trapped in holes. The plastic is thus subjected to more intense mechanical wear, resulting in progressively larger holes (Ravishankar et al., 2018). In addition, the organisms select better sheltered holes as living habitats. The interaction between organisms and plastics accelerates the process of plastic fragmentation (Zheng et al., 2023). When exposed to plastic fragments surface, the fillers inside the holes were more likely to fall out. Eventually, the apparent density of fragmented plastics was altered.

Given the coastal occurrence, plastics stranded on the beach might

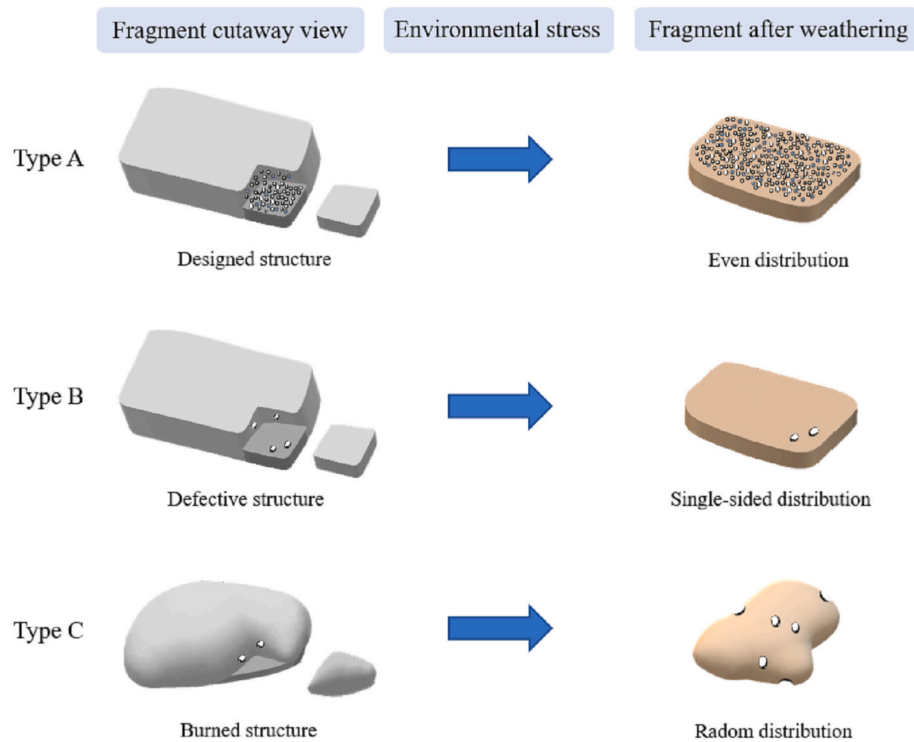

Fig. 5. Distribution pattern of holes on the surface and cross-section of plastics.

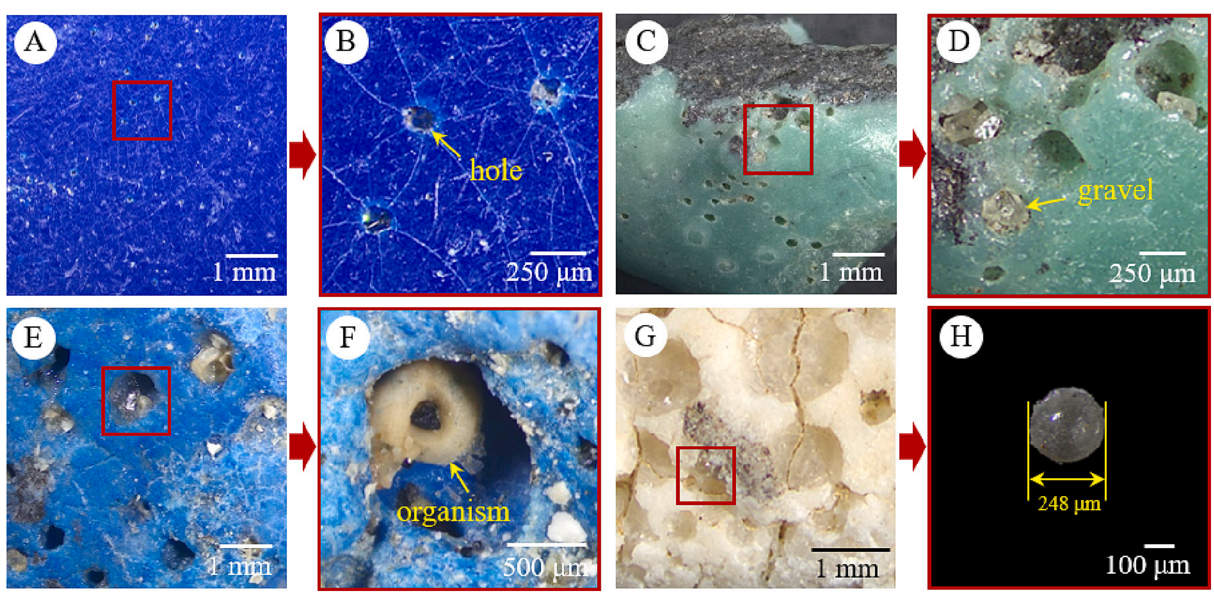

Fig. 6. Optical images of holes on plastics surface. Plastic surface with holes (A) and cracks extended outward from holes (B). Plastic surface with holes (C) and gravels in holes (D). Plastic surface with holes (E) and organisms in holes (F). Filler embedded in a hole (G) and a filler falling out of the hole (H).

be washed out and returned to the sea during storm actions (Nakajima et al., 2022). The formation of holes and the accompanying phenomena also lead to changes in plastic fate in the environment. Generally, the sinking behavior of plastics depends on their density in the water (Pabortsava and Lampitt, 2020; Subías-Baratau et al., 2022). Most plastic polymers are positively buoyant, so they float on the surface or are suspended at an equal level of density in the water column (Geyer et al., 2017; Hidalgo-Ruz et al., 2012). This study suggested that plastics with holes on surfaces may be changed the sinking process in the marine environment (Fig. 7). When holes are filled with water, the plastic becomes denser and slightly sinks into the water column. The fouling significantly changed the density and settling state of plastics (Amaral-Zettler et al., 2021). The total weight of the plastic increased with the amount of biofouling. When sands and gravels become trapped in the holes, the weight of plastic increases dramatically. Plastic with a high concentration of contaminants on the surface will gradually sink. Over 90 % of marine plastics eventually end up on the seafloor (Koelmans et al., 2017).

Size and irregular shapes (surface-area ratio) typically also affect the sinking behavior of plastics (Waldschläger and Schüttrumpf, 2019). Plastics with small sizes, their density depends on many factors, including the attached contaminant load (Kooi et al., 2017). Given

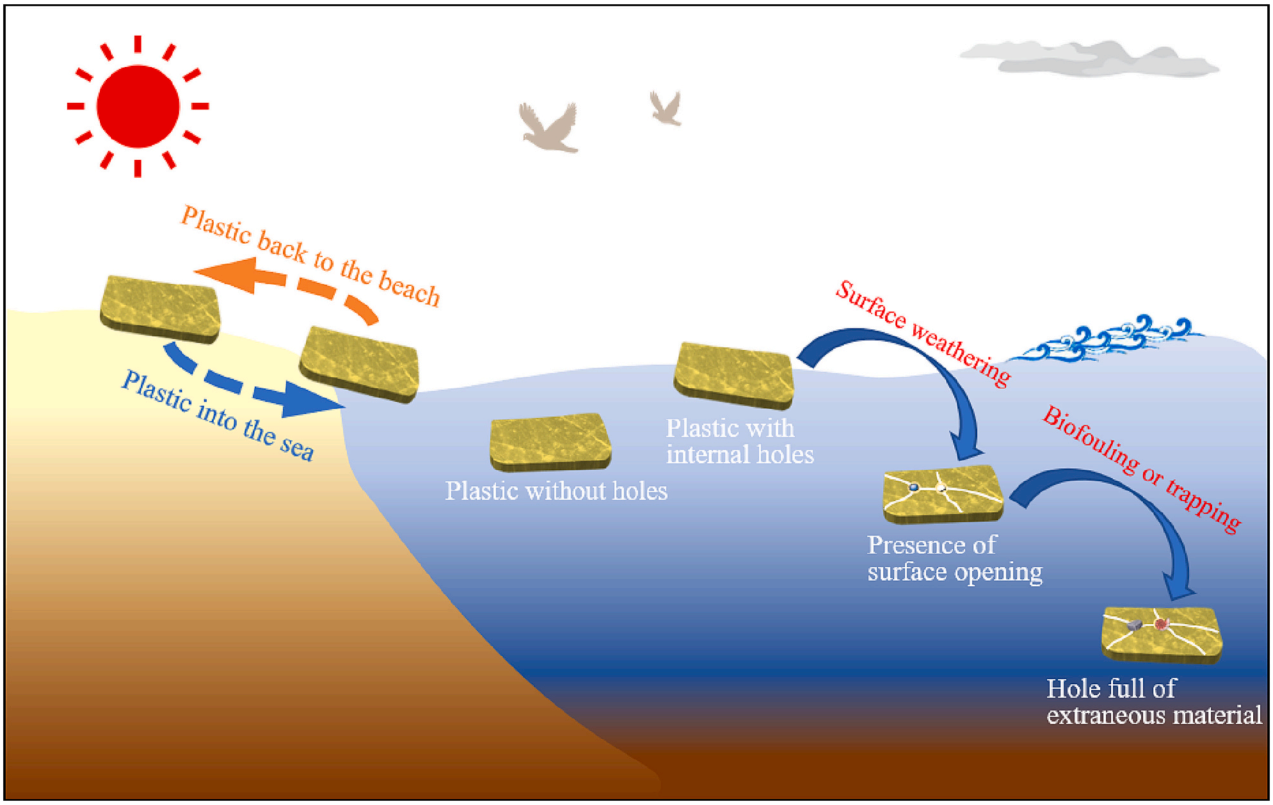

Fig. 7. Effects of holes on plastic surfaces in the environment.

similar volumes and densities, the smoother plastics experience less resistance and thus have larger sinking velocities (Khatmullina and Isachenko, 2017). While the ecological impact of sunken plastics is not entirely clear, there is evidence or both lethal and sub-lethal effects of micro and nanoplastics have been previously identified (López-Rojo et al., 2020; Pikuda et al., 2022). For example, plastics accumulate into patches and gyres around islands both at the surface, being transported by currents or undergoing fragmentation by erosion or UV radiation and breakdown to be deposited in the seafloor by marine snow or deep-sea current (Mohrig, 2020). Ingestion of microplastics by water column organisms and benthic organisms in the seafloor sediments may result in altered metabolic and reproductive endpoints (Galloway et al., 2017).

Regardless of their occurrence and composition, fragments should be considered important intermediates in the dynamics of plastic fragmentation in the environment. The tiny and/or deep holes in plastics set the stage for the formation of larger holes on the surface (Civancik-Uslu et al., 2018; Fan et al., 2021; Qin et al., 2022). Environmental conditions accelerate the formation and enlargement of holes on plastic surfaces. The presence of holes not only changed the external morphological characteristics of plastic fragments but also affected the weathering process and the existing state of plastics in the environment (Amaral-Zettler et al., 2021; Hidalgo-Ruz et al., 2012). Holes bear more information about the release of fillers and the embedment of contaminants, a particular area that lacks information at the global scale. In previous studies, fragmented plastic and shed fillers have been proven to contribute to primary and secondary microplastic contamination in the environment (Brebu, 2020; Laskar and Kumar, 2019; Wu, 2022). Our findings emphasized that holes in the surface of the plastic could cause additional unknown environmental impacts that require assessment.

4. Conclusion

This study describes the presence of holes on the surfaces of plastics exposed to environmental conditions in beaches spread worldwide. The occurrence of external holes on the surfaces was a combination of design or defects of the material itself during the manufacturing process and the environmental conditions they are exposed to. The distribution pattern of holes on plastics surface can be divided into even, single-sided, and random categories. The external holes promoted crack formation, organisms hosting, sand trapping, and filler losing, which in turn changed the density and fate of plastics. Our study indicates that the holes on plastic in the environment were obvious deformation of weathering plastics. Given the implications that fragmentation and degradation of plastic debris have (e.g. incorporation into marine food webs), this topic should receive more attention and investment to assess density changes and improve mathematical distribution models on macro- and microplastics.

CRediT authorship contribution statement

Yifan Zheng: Conceptualization, Data curation, Investigation, Methodology, Visualization, Validation, Writing – original draft. **Mohamed Hamed:** Investigation. **Gabriel Enrique De-la-Torre:** Investigation, Methodology. **João Frias:** Investigation, Writing – review & editing. **Mui-Choo Jong:** Investigation, Writing – review & editing. **Prabhu Kolandhasamy:** Investigation, Writing – review & editing. **Suchana Chavanich:** Investigation. **Lei Su:** Investigation, Methodology. **Hua Deng:** Investigation, Methodology. **Wenjun Zhao:** Data curation. **Huahong Shi:** Resources, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115180.

References

Amaral-Zettler, L.A., Zettler, E.R., Mincer, T.J., Klaassen, M.A., Gallager, S.M., 2021. Biofouling impacts on polyethylene density and sinking in coastal waters: a macro/micro tipping point? Water Res. 201, 117289.
Arp, H.P.H., Kühnel, D., Rummel, C., Macleod, M., Potthoff, A., Reichelt, S., Rojo-Nieto, E., Schmitt-Jansen, M., Sonnenberg, J., Toorman, E., Jahnke, A., 2021. Weathering plastics as a planetary boundary threat: exposure, fate, and hazards. Environ. Sci. Technol. 55, 7246–7255.
Banerjee, R., Ray, S.S., 2020. Foamability and special applications of microcellular thermoplastic polymers: a review on recent advances and future direction. Macromol. Mater. Eng. 305, 2000366.
Brebu, M., 2020. Environmental degradation of plastic composites with natural fillers: a review. Polymers 12, 166.
Cao, W.X., Wang, Y.F., Zhou, P.Y., Yang, X.B., Wang, K., Pang, B.J., Chi, R.Q., Su, Z.Q., 2019. Microstructural material characterization of hypervelocity-impact-induced pitting damage. Int. J. Mech. Sci. 163, 105097.
Civancik-Uslu, D., Ferrer, L., Puig, R., Fullana-i-Palmer, P., 2018. Are functional fillers improving environmental behavior of plastics? A review on LCA studies. Sci. Total Environ. 626, 927–940.
Cogulet, A., Blanchet, P., Landry, V., Morris, P., 2018. Weathering of wood coated with semi-clear coating: study of interactions between photo and biodegradation. Int. Biodeterior. Biodegradation 129, 33–41.
Corcoran, P.L., Jazvac, K., 2020. The consequence that is plastiglomerate. Nat. Rev. Earth Environ. 1, 6–7.
Dávila, L.P., Erhart, P., Bringa, E.M., Meyers, M.A., Lubarda, V.A., Schneider, M.S., Becker, R., Kumar, M., 2005. Atomistic modeling of shock-induced void collapse in copper. Appl. Phys. Lett. 86, 161902.
De-la-Torre, G.E., Dioses-Salinas, D.C., Pizarro-Ortega, C.I., Santillán, L., 2021. New plastic formations in the Anthropocene. Sci. Total Environ. 754, 142216.
Deng, H., Su, L., Zheng, Y.F., Du, F.N., Liu, Q.X., Zheng, J., Zhou, Z.W., Shi, H.H., 2022. Crack patterns of environmental plastic fragments. Environ. Sci. Technol. 56, 6399–6414.
Edo, C., Tamayo-Belda, M., Martínez-Campos, S., Martín-Betancor, K., González-Pleiter, M., Pulido-Reyes, G., García-Ruiz, C., Zapata, F., Leganés, F., Fernández-Piñas, F., Rosal, R., 2019. Occurrence and identification of microplastics along a beach in the biosphere reserve of Lanzarote. Mar. Pollut. Bull. 143, 220–227.
Ellrich, J.A., Ehlers, S.M., 2022. Field observations in pebble beach habitats link plastiglomerate to pyroplastic via pebble clasts. Mar. Pollut. Bull. 174, 113187.
Fan, X.L., Gan, R., Liu, J.Q., Xie, Y., Xu, D.Z., Xiang, Y., Su, J.K., Teng, Z., Hou, J., 2021. Adsorption and desorption behaviors of antibiotics by tire wear particles and polyethylene microplastics with or without aging processes. Sci. Total Environ. 771, 145451.
Feng, Q., An, C.J., Chen, Z., Yin, J.N., Zhang, B.Y., Lee, K., Wang, Z., 2022. Investigation into the impact of aged microplastics on oil behavior in shoreline environments. J. Hazard. Mater. 421, 126711.
Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol. 1, 0116.
Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782.
Halle, A.T., Ladirat, L., Gendre, X., Goudouneche, D., Pusineri, C., Routaboul, C., Tenailleau, C., Duployer, B., Perez, E., 2016. Understanding the fragmentation pattern of marine plastic debris. Environ. Sci. Technol. 50, 5668–5675.
Halle, A.T., Ladirat, L., Martignac, M., Mingotaud, A.F., Boyron, O., Perez, E., 2017. To what extent are microplastics from the open ocean weathered? Environ. Pollut. 227, 167–174.
Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075.
Horne, F.J., Liggat, J.J., MacDonald, W.A., Sankey, S.W., 2020. Photo-oxidation of poly (ethylene terephthalate) films intended for photovoltaic backsheet. J. Appl. Polym. Sci. 137, 48623.
Hu, J.Y., Lee, F.Y., Hu, J.Y., 2023. Characteristics and behaviors of microplastics undergoing photoaging and advanced oxidation processes (AOPs) initiated aging. Water Res. 16, 119628.
Khatmullina, L., Isachenko, I., 2017. Settling velocity of microplastic particles of regular shapes. Mar. Pollut. Bull. 114, 871–880.
Koelmans, A.A., Kooi, M., Law, K.L., Sebille, E.V., 2017. All is not lost: deriving a top-down mass budget of plastic at sea. Environ. Res. Lett. 12, 114028.
Kooi, M., Nes, E., Scheffer, M., Koelmans, A.A., 2017. Ups and downs in the ocean: effects of biofouling on vertical transport of microplastics. Environ. Sci. Technol. 51, 7963–7971.
Laskar, N., Kumar, U., 2019. Plastics and microplastics: a threat to environment. Environ. Technol. Innov. 14, 100352.
Li, Y.Q., Wang, T., Zhou, M., 2021. Impact response characteristics and meso-evolution mechanism of functionally gradient brittle materials with pore hole damage. Compos. Struct. 256, 112989.
Liu, P., Qian, L., Wang, H.Y., Zhan, X., Lu, K., Gu, C., Gao, S.X., 2019. New insights into the aging behavior of microplastics accelerated by advanced oxidation processes. Environ. Sci. Technol. 53, 3579–3588.
Liu, Z.Y., Zhu, Y.J., Lv, S.S., Shi, Y.X., Dong, S.F., Yan, D., Zhu, X.S., Peng, R., Keller, A. A., Huang, Y.X., 2022. Quantifying the dynamics of polystyrene microplastics UV-aging process. Environ. Sci. Technol. Lett. 9, 50–56.
Long, M., Paul-Pont, I., Hégaret, H., Moriceau, B., Lambert, C., Huvet, A., Soudant, P., 2017. Interactions between polystyrene microplastics and marine phytoplankton lead to species-specific hetero-aggregation. Environ. Pollut. 228, 454–463.
López-Rojo, N., Pérez, J., Alonso, A., Correa-Araneda, F., Boyero, L., 2020. Microplastics have lethal and sublethal effects on stream invertebrates and affect stream ecosystem functioning. Environ. Pollut. 259, 113898.
Mohrig, D., 2020. Deep-ocean seafloor islands of plastics. Science 368, 1055.
Monte, C.D., Locritani, M., Merlino, S., Ricci, L., Pistolesi, A., Bronco, S., 2022. An in situ experiment to evaluate the aging and degradation phenomena induced by marine environment conditions on commercial plastic granules. Polymers 14, 1111.
Najafi, S.K., 2013. Use of recycled plastics in wood plastic composites: a review. Waste Manag. 33, 1898–1905.
Nakajima, R., Miyama, T., Kitahashi, T., Isobe, N., Nagano, Y., Ikuta, T., Oguri, K., Tsuchiya, M., Yoshida, T., Aoki, K., Maeda, Y., Kawamura, K., Suzukawa, M., Yamauchi, T., Ritchie, H., Fujikura, K., Yabuki, A., 2022. Plastic after an extreme storm: the typhoon-induced response of micro- and mesoplastics in coastal waters. Front. Mar. Sci. 8, 806952.
Pabortsava, K., Lampitt, R.S., 2020. High concentrations of plastic hidden beneath the surface of the Atlantic Ocean. Nat. Commun. 11, 4073.
Pikuda, O., Dumont, E.R., Matthews, S., Xu, E.G., Berk, D., Tufenkji, N., 2022. Sub-lethal effects of nanoplastics upon chronic exposure to Daphnia magna. J. Hazard Mater. Adv. 7, 100136.
Qin, Q.Y., Yang, Y.D., Yang, C.F., Zhang, L.H., Yin, H.Y., Yu, F., Ma, J., 2022. Degradation and adsorption behavior of biodegradable plastic PLA under conventional weathering conditions. Sci. Total Environ. 842, 156775.
Qiu, X.R., Ma, S.R., Zhang, J.X., Fang, L.C., Guo, X.T., Zhu, L.Y., 2022. Dissolved organic matter promotes the aging process of polystyrene microplastics under dark and ultraviolet light conditions: the crucial role of reactive oxygen species. Environ. Sci. Technol. 56, 10149–11016.
Rabesandratana, T., 2021. Report traces surge in ocean plastic studies. Science 372, 1249.
Ranjan, V.P., Goel, S., 2021. Recyclability of polypropylene after exposure to four different environmental conditions. Resour. Conserv. Recycl. 169, 105494.
Ravishankar, K., Ramesh, P.S., Sadhasivam, B., Raghavachari, D., 2018. Wear-induced mechanical degradation of plastics by low-energy wet-grinding. Polym. Degrad. Stab. 158, 212–219.
Sarac, B., Schroers, J., 2013. Designing tensile ductility in metallic glasses. Nat. Commun. 4, 2158.
Sarkar, A.K., Rubin, A.E., Zucker, I., 2021. Engineered polystyrene-based microplastics of high environmental relevance. Environ. Sci. Technol. 55, 10491–10501.
Seo, J.H., Ohm, W.S., Cho, S.H., Cha, S.W., 2011. Combined effects of psaturation pressure and gas desorption on foaming characteristics of microcellular plastics. Polym.-Plast. Technol. Eng. 50, 1399–1404.
Serra-Gonçalves, C., Lavers, J.L., Bond, A.L., 2019. Global review of beach debris monitoring and future recommendations. Environ. Sci. Technol. 53, 12158–12167.
Subías-Baratau, A., Sanchez-Vidal, A., Martino, E.D., Figuerola, B., 2022. Marine biofouling organisms on beached, buoyant and benthic plastic debris in the Catalan Sea. Mar. Pollut. Bull. 175, 113405.
Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., Mcgonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838.
Waldschläger, K., Schüttrumpf, H., 2019. Effects of particle properties on the settling and rise velocities of microplastics in freshwater under laboratory conditions. Environ. Sci. Technol. 53, 1958–1966.
Welden, N.A., Lusher, A.L., 2017. Impacts of changing ocean circulation on the distribution of marine microplastic litter. Integr. Environ. Assess. 13, 483–487.
Wu, N., 2022. Tracing microplastic footprints through the plastisphere. Nat. Rev. Earth Environ. 3, 498.
Wu, X.W., Liu, P., Wang, H.Y., Huang, H.Y., Shi, Y.Q., Yang, C.F., Gao, S.X., 2021. Photo aging of polypropylene microplastics in estuary water and coastal seawater: important role of chlorine ion. Water Res. 202, 117396.
Xiang, L.H., Pan, J.Y., Chen, S.Y., 2018. Analysis on the stress corrosion crack inception based on pit shape and size of the FV520B tensile specimen. Results Phys. 9, 463–470.
Yu, Y.X., Xu, P.P., Chang, M.M., Chang, J.M., 2018. Aging properties of phenol-formaldehyde resin modified by bio-oil using UV weathering. Polymers 10, 1183.

Zhang, S., Zhu, S., Han, K.Q., Feng, X.L., Ma, Y., Yu, M.H., Reiter, G., 2013. Toughening plastics by crack growth inhibition through unidirectionally deformed soft inclusions. Polymer 54, 6019–6025.
Zheng, Y.F., Li, J.X., Cao, W., Liu, X.H., Jiang, F.H., Ding, J.F., Yin, X.F., Sun, C.J., 2019. Distribution characteristics of microplastics in the seawater and sediment: a case study in Jiaozhou Bay, China. Sci. Total Environ. 674, 27–35.
Zheng, Y.F., Zhu, J.M., Li, J.J., Li, G.L., Shi, H.H., 2023. Burrowing invertebrates induce fragmentation of mariculture Styrofoam floats and formation of microplastics. J. Hazard. Mater. 447, 130764.
Zhou, Q., Zhang, H.B., Fu, C.C., Zhou, Y., Dai, Z.F., Li, Y., Tu, C., Luo, Y.M., 2018. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. Geoderma 322, 201–208.