

Preliminary Investigation of Atmospheric Deposition of Microplastics in a Coastal Suburban Area

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Abstract: Microplastics (MPs) are contaminants found in various environmental matrices. Their small size and low weight make them highly mobile and easily transported through the atmosphere by the wind before settling through deposition. This study presents a preliminary investigation of the abundance and physical characteristics of MPs in atmospheric deposition samples from a coastal suburban area. Passive sampling was conducted from November 2021 to January 2022. The findings revealed microplastic contamination in all deposition samples, with an average abundance of 126.17 ± 90.9 MP/m²/d, ranging between 18.32 and 372.41 MP/m²/d. The highest abundance was recorded in December 2021 (262.52 ± 123.27 MP/m²/d), followed by November 2021 (215.71 ± 90.08 MP/m²/d) and January 2022 (152.63 ± 53.74 MP/m²/d). Transparent fibers were the most common microplastic shape. Surface morphology analysis using scanning electron microscopy revealed evidence of weathering, with signs of flakes, adhering particles, cracks and fractures on the MP surfaces. These findings provide fundamental insights into the abundance, physical characteristics and morphology of airborne MPs, emphasizing the need for further studies to understand their behavior, particularly in coastal environments.

Keywords: Microplastics, atmospheric deposition, shape, surface morphology, coastal area.

1. Introduction

Plastic pollution, such as microplastics (MPs), has become a major global issue because of its potential threats to various living organisms, including humans. Microplastics can enter the body through ingestion or inhalation, and may cause physical damage and trigger inflammation (Koelmans et al., 2017; Wright & Kelly, 2017). Due to their small size and large specific surface area, MPs facilitate the transport of hazardous chemicals, such as heavy metals and persistent organic pollutants (Gouin, 2021), by providing surfaces that promote contaminant adsorption, which may, in turn, increase their bioavailability and toxicity. Inefficient plastic recycling processes and improper waste management further contribute to the release of plastics into the environment (OECD, 2022). Plastics in the environment are broadly classified as macroplastics (greater than 5 mm) or microplastics (less than 5 mm). Plastic debris frequently breaks down into smaller particles through chemical, biological and physical processes. This breakdown results in an increasing abundance of MPs, classified as secondary MPs. Meanwhile, primary MPs are produced in small sizes for various applications, including personal care items (e.g., scrubbing agents), industrial manufacturing (e.g., plastic pellets or nurdles) and synthetic textiles (e.g., plastic fibers).

Recent studies have reported substantial accumulations of MPs in both aquatic and terrestrial ecosystems (Ali et al., 2024; Pal et al., 2024; Razak et al., 2023; Rillig & Lehmann, 2020). Once released, MPs can persist in the environment and become airborne, with wind facilitating their transport, deposition and long-distance dispersal. Research has shown that airborne MPs are present even in remote regions, including the French Pyrenees and the Arctic Ocean, far from visible sources of MPs (Allen et al., 2019; Bergmann et al., 2022). Such observations highlight the capacity of MPs for long-range atmospheric transport and raise concerns about their accumulation and ecological impacts in pristine environments. Moreover, the fate of airborne MPs is influenced by urbanization levels and by temporal and spatial variability. Klein et al. (2023) reported higher MP deposition rates in urban areas than in rural regions in Northern Germany over a one-year period, which could be explained by population density. Similar patterns have been observed in other regions, including China (Luo et al., 2024), India (Parashar & Hait, 2023), Korea (Chang et al., 2023), Mexico (Shruti et al., 2022) and Thailand (Sarathana & Winijkul, 2023), where population density and human activities influence the distribution of airborne MPs.

Understanding the characteristics of airborne MPs, including shape, color, size and abundance, is crucial for interpreting their behavior and potential impacts. Comprehensive data on these features can aid in identifying MP emission sources, thereby

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enabling targeted mitigation strategies. Furthermore, such data are essential for assessing potential health risks associated with inhalation exposure. In this study, we investigated the presence of MPs in atmospheric deposition samples from a coastal suburban area, which forms a dynamic interface between terrestrial and marine environments. This setting is influenced by both land-based anthropogenic activities and marine sources, reflecting contributions from multiple source pathways. The collected particles were classified based on color, shape and surface morphology. The results provide baseline data that contribute to current knowledge of airborne microplastic pollution and support future research on the behavior of airborne MPs, especially in coastal areas.

2. Material and Methods

Study Area

Atmospheric deposition sampling was conducted on the rooftop of the Faculty of Science and Marine Environment (FSSM) (5.412°N, 103.086°E) building in Universiti Malaysia Terengganu (UMT). The sampling site is situated in a suburban coastal area of Kuala Nerus, in the state of Terengganu, Malaysia. The site is adjacent to the South China Sea, as shown in Figure 1. This coastal setting forms a transitional zone between land and sea, influenced by surrounding human activities such as academic, residential and traffic-related sources, as well as marine processes, including sea spray and coastal resuspension. In addition, the site experiences seasonal monsoon conditions, characterized by wind patterns and precipitation, which may further influence the transport and deposition of airborne MPs from both inland and marine environments.

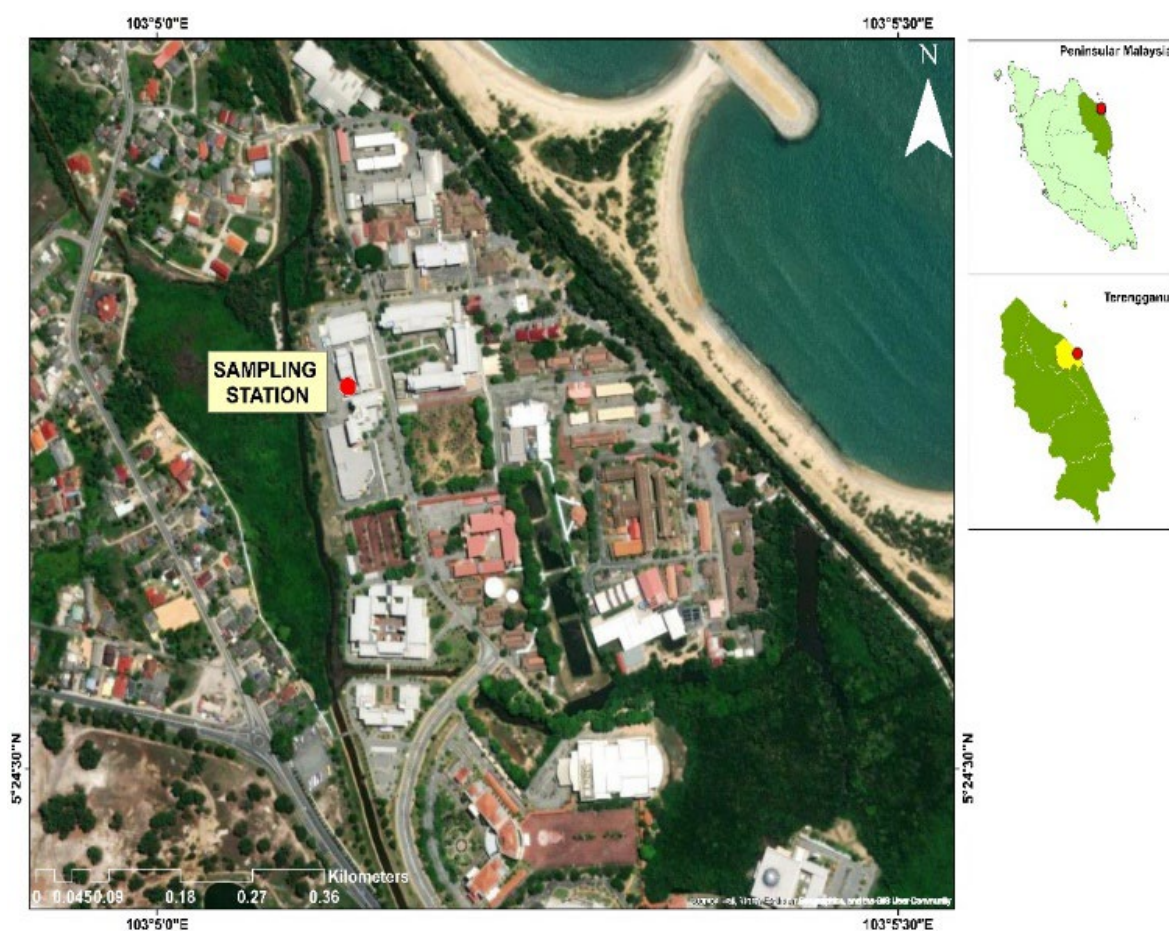


Figure 1. Map of the study area (red dot indicates the sampling site).

Sample Collection and Pre-treatment

A particulate fallout collector, as described by Dris et al. (2016), was used to collect total atmospheric deposition. The collector consisted of a stainless steel funnel for channeling and a glass bottle for sample collection. Samples of microplastic deposition were collected over three months, from November 2021 to January 2022 ($n=15$), during the Northeast monsoon season, which included several rainfall events. For each month, five glass

bottles were deployed in one sampling round and exposed for 14 days. All samples were labeled according to the sampling month and replicate number, namely November (N1 – N5), December (D1 – D5) and January (J1 – J5). After sampling, the glass bottles containing the samples were wrapped in aluminum foil and transported to the laboratory for further analysis. The samples were rinsed with 150 mL of Milli-Q water and transferred to glass beakers. The samples were then pre-treated with 20 mL of 30%

(v/v) hydrogen peroxide (H_2O_2) to remove natural organic matter. The mixtures were stirred continuously at 200 rpm for 1 hour while heated on a hotplate at 70°C . The samples were then left to cool for another hour before being filtered through a vacuum pump filtration system with 47 mm filters (Whatman glass fiber). The filters that contained trapped MPs were finally placed in clean glass Petri dishes. Then, the Petri dishes were wrapped in pinhole aluminum foil and dried overnight in a desiccator before visual sorting (Prata et al., 2020).

Quantification and Identification of Microplastics

Microplastic particles were visually identified and counted using a stereomicroscope (ZEISS Stemi 305), following the method described by Chenappan et al. (2024). The Petri dishes were only uncovered when necessary to minimize the risk of cross-contamination. The particles were then sorted manually based on shape and color using stainless steel tweezers. A hot needle test was conducted during the sorting process to confirm that the suspected particles were MPs. This test involved scorching the particles with a hot needle, and if they are truly MPs, they tend to curl or melt, whereas non-plastic materials remain unaffected. The hot needle test was performed using a needle that had been heated to a high temperature as described in Tunçer et al. (2018).

Scanning Electron Microscopy-Energy Dispersive X-ray Spectroscopy (SEM-EDX) analysis

The surface morphology of microplastic particles in the deposition samples was examined using SEM-EDX (Model TESCAN VEGA S5000). For SEM analysis, fibers were selected because they represented the dominant shape observed in the deposition samples. Pellets, although less abundant, were also included to allow morphological comparison between particle shapes. Particle selection was performed within these categories to assess surface features associated with environmental weathering and aging processes. Selected microplastic particles were mounted on aluminum stubs with conductive carbon tape. The stubs were then coated with a thin layer of evaporated gold to increase conductivity. The SEM was operated at an accelerating voltage of 15 kV, with magnifications of $80\times$ and $11,000\times$. The detector working distance was kept at approximately 2 mm to obtain high-resolution images.

Data Analysis

Microplastic concentrations were analyzed using appropriate statistical methods to test for differences among sampling periods. Mean concentrations were calculated to represent monthly variations in microplastic deposition. Differences in MP concentrations were considered statistically significant at $p < 0.05$. A normality test was performed on the data distributions using the Shapiro-Wilk test. As the data did not follow a normal distribution, the Kruskal-Wallis H-test was used to evaluate differences in microplastic concentrations among independent sample groups. Descriptive statistics were computed using XLSTAT software (version 2019, USA) and RStudio (2024.04.2-764).

Quality Control and Quality Assurance

Necessary measures were adopted to minimize contamination during the sampling and analytical procedures. The use of plastic materials was avoided wherever possible during sample handling and processing. Appropriate personal protective equipment, including nitrile gloves and a cotton laboratory coat, was worn when handling the samples. All glassware and apparatus were thoroughly washed with Milli-Q water and covered with aluminum foil before and after use. Procedural blank tests were performed to check for background contamination. Blank samples underwent the same procedures as the deposition samples. A Petri dish with a clean filter was used throughout sample processing to assess the risk of airborne contamination.

3. Results and Discussion

Abundance of Atmospheric Microplastics

Microplastic particles were found in all atmospheric deposition samples ($n=15$) collected over three months, with a total of 310 MPs identified. As shown in Figure 2, the highest deposition rate was recorded in December ($372.41 \text{ MP/m}^2/\text{d}$, sample D2), whereas the lowest was observed in November ($18.32 \text{ MP/m}^2/\text{d}$, sample N5). The median deposition rate across all samples was $103.79 \text{ MP/m}^2/\text{d}$. The highest mean deposition rate occurred in December 2021 ($262.52 \pm 123.27 \text{ MP/m}^2/\text{d}$), followed by November 2021 ($215.71 \pm 90.08 \text{ MP/m}^2/\text{d}$) and January 2022 ($152.63 \pm 53.74 \text{ MP/m}^2/\text{d}$), with no significant differences between months (Kruskal-Wallis $\chi^2 = 5.99$, $df = 2$, $p = 0.34$). The lack of statistically significant differences in microplastic distribution between months may be due to several factors. Regionally, consistent meteorological conditions associated with the Northeast monsoon, including similar wind regimes, rainfall patterns and atmospheric transport processes, may have reduced temporal variability. In addition, this study is a preliminary assessment with a limited sample size of 5 observations per month, which reduces statistical power and increases the probability of a Type II error, potentially obscuring subtle temporal differences. The absence of significant monthly differences suggests that microplastic deposition was relatively consistent throughout the sampling period, despite fluctuations in individual sampling events. This implies that short-term fluctuations may have been influenced by episodic factors rather than distinct monthly patterns during the Northeast monsoon season. This finding is consistent with a previous study by Hee et al. (2023), which reported airborne MP deposition rates ranging from 114 to $689 \text{ MP/m}^2/\text{d}$ in the Kuala Nerus area. MPs in the air are primarily a result of human activities and can be carried by wind over long distances, depending on particle size and density. Because the sampling site lies in a coastal region, the presence of MPs is likely influenced by local sources such as synthetic textiles, fishing nets, food packaging and other plastic materials associated with human activities. In addition, sea-spray droplets containing MPs may contribute to atmospheric inputs in coastal environments (Habibi et al., 2024). Marine environments, which act as sinks for MPs, can also serve as secondary sources of atmospheric MPs through ocean-atmosphere exchange

processes. Trainic et al. (2020) showed that air bubbles generated by breaking waves and rainfall at the air-sea interface can release MPs into the atmosphere, further contributing to airborne transport.

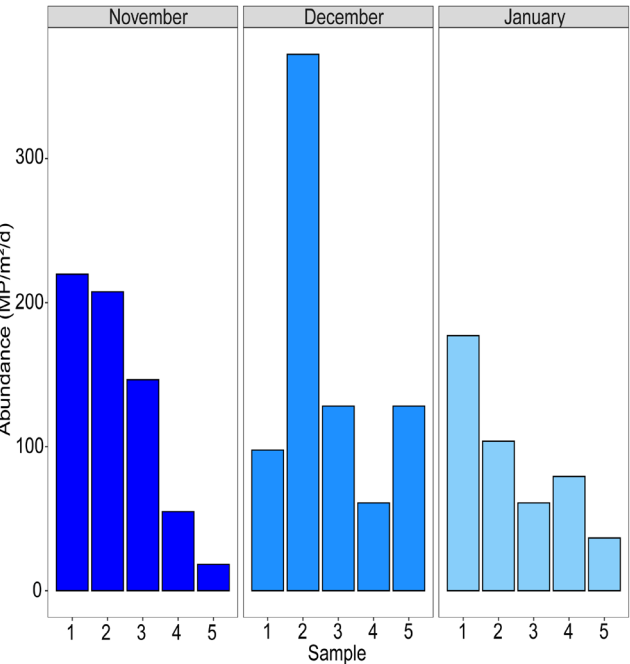


Figure 2. Microplastic abundance in deposition samples (n=15) in each month.

Table 1 compares the microplastic deposition rates observed in this study with those reported in previous studies. In urban areas, airborne MP abundances are generally high, ranging from 71 to 917 MP/m²/d in Ho Chi Minh, Vietnam (Truong et al., 2021), 575 to 1008 MP/m²/d in London, United Kingdom (Wright et al., 2020), and 469.21 to 12,611.46 MP/m²/d in Shanghai, China (Jia et al., 2022), where high population density, traffic intensity and industrial activities contribute substantially to atmospheric MP sources. In contrast, studies conducted in remote regions such as the Pyrenees Mountains have reported deposition rates between 402 and 462 MP/m²/d, highlighting the role of long-range atmospheric transport despite the absence of local sources (Allen et al., 2019). In the present coastal study area, MP deposition rates were lower than those reported in urban and remote regions but higher than those observed in Jakarta, Indonesia (Purwiyanto et al., 2022), a densely populated city. This finding suggests that factors beyond population density may influence MP deposition, including local emission characteristics, which in coastal areas involve activities such as fishing and tourism, in addition to meteorological conditions and sampling methodologies. The deposition rates obtained in this study were comparable with those reported by Hee et al. (2023), indicating relatively consistent MP deposition patterns in the Kuala Nerus coastal area. Overall, variations in airborne MP abundances among studies may be attributed not only to differences in sampling environments (e.g., urban, remote and coastal settings), population density and anthropogenic activities, but also to seasonal variability and methodological approaches used in sample collection and processing.

Table 1. Comparison of microplastic deposition rates, shapes and colors.

Location	Site type	Deposition rate (MP/m²/d)	Shape	Color	Reference
Kuala Malaysia	Nerus, Suburban coastal	18.32 to 372.41	Fiber, fragment, pellet	Black, transparent, blue, pink, purple, brown, yellow, red	This study
Kuala Malaysia	Nerus, Suburban coastal	114 to 689	Fragments	N/A	Hee et al., 2023
Jakarta, Indonesia	Urban	6 to 31	Fiber, fragment, foam	N/A	Purwiyanto et al., 2022
Shanghai, China	Urban	469.21 to 12,611.46	Fiber, film, granular	N/A	Jia et al., 2022
Ho Chi Minh, Vietnam	Urban	71 to 917	Fiber, fragment	Red, blue, green, gray, black	Truong et al., 2021
Gdynia, Poland	Coastal urban	0 to 30	Fibers, fragments, films	N/A	Szewc et al., 2021
London, UK	Urban	575 to 1008	Fibers, fragments, films, granules, foams	N/A	Wright et al., 2020
Pyrenees Mountains, France	Remote	402 to 462	Fragments, films, fibers	N/A	Allen et al., 2019

Characteristics of Microplastic Particles: Shape and Color

Figure 3 shows images of the MPs identified in the collected atmospheric deposition samples. Overall, the samples consisted of fibers (97.74%) in various sizes and colors, followed by fragments (1.94%) and pellets (0.32%). The dominance of fibers was consistent across the three-month sampling (Figure 4) and agreed with findings from previous studies (Chenappan et al., 2024; Szewc et al., 2021). The higher percentage of fibers in the atmospheric samples can be attributed to their lower density and aerodynamic properties. Furthermore, fibers are easily shed from textile products, and the widespread availability of fiber sources such as clothing, tire wear and industrial activities emphasizes

their major contribution to microplastic contamination in the air (Zhang et al., 2020). Although the shapes of MPs can help determine their sources in a given area, further analyses are required to identify the emission pathways for atmospheric MPs. Both shape and particle size of MPs play a key role in determining their presence in the atmosphere, which influences their settling rates and the distance traveled while suspended. However, size distribution was not reported in this study because less than 50% of the identified particles remained available for size measurement, and the dataset was considered insufficient to represent the overall MP count.

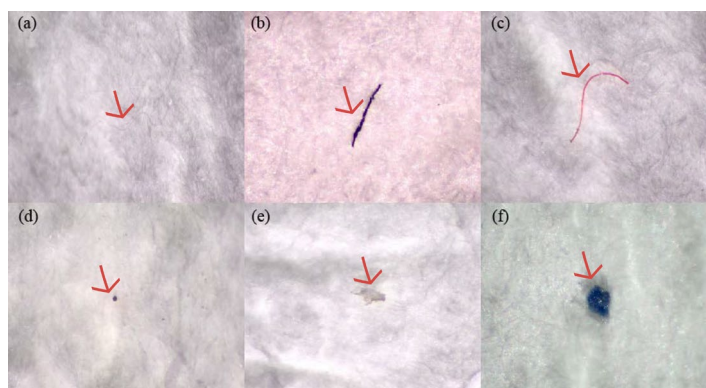


Figure 3. Images of microplastics extracted from atmospheric deposition samples, (a–c) transparent, black and red microfibers, (d) black pellet, (e) transparent fragment and (f) blue fragment.

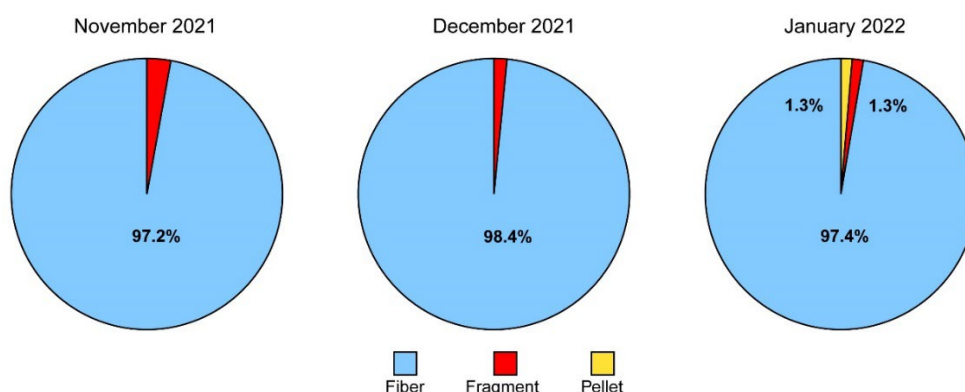


Figure 4. The percentage of microplastic shapes in deposition samples for each month.

The distribution of airborne MP colors is shown in Figure 5. Overall, particles were observed in eight colors: black, transparent, blue, pink, purple, brown, yellow and red. However, all eight colors were detected only in samples collected in December, whereas samples from November and January exhibited seven and five colors, respectively, indicating slight temporal variability in particle inputs. This variation may reflect short-term fluctuations in atmospheric transport, wet deposition efficiency or mixed emission sources rather than a clear seasonal pattern, because microplastic color is not directly governed by meteorological conditions. Among the identified colors, transparent MPs were the most abundant, ranging from 32.6% to 48%, whereas brown MPs were the least abundant (0.32%). This

trend is consistent with earlier studies, which reported transparent particles as the dominant color of airborne MPs (Chenappan et al., 2024; Parashar & Hait, 2023). The predominance of transparent MPs probably reflects the widespread use of colorless single-use plastic products.

In addition, transparent particles may originate from weathered plastics, where environmental exposure can lead to pigment degradation and color fading. This process is primarily driven by photo-oxidation, in which ultraviolet (UV) radiation induces polymer chain scission and the formation of carbonyl groups, resulting in the breakdown of pigments and alteration of optical properties (Andrady et al., 2023). Furthermore, particle color may be altered by laboratory pre-treatment processes, particularly

during wet peroxide oxidation. In this process, hydrogen peroxide decomposes to generate highly reactive hydroxyl radicals, which oxidize organic matter and polymer surfaces, potentially degrading pigments and modifying the original color of MPs (Hurley et al., 2018; Jeong et al., 2023; Nakahashi et al., 2023). Colored MPs, such as black, blue, red and yellow particles, provide further insight into potential sources. For example, black particles

are commonly linked to tire wear or industrial materials (Reynolds et al., 2024), whereas blue and red fibers are frequently associated with clothing and household fabrics (Zhang et al., 2020). In coastal environments, colored MPs may also originate from fishing-related materials and marine debris, reflecting the influence of terrestrial and marine activities.

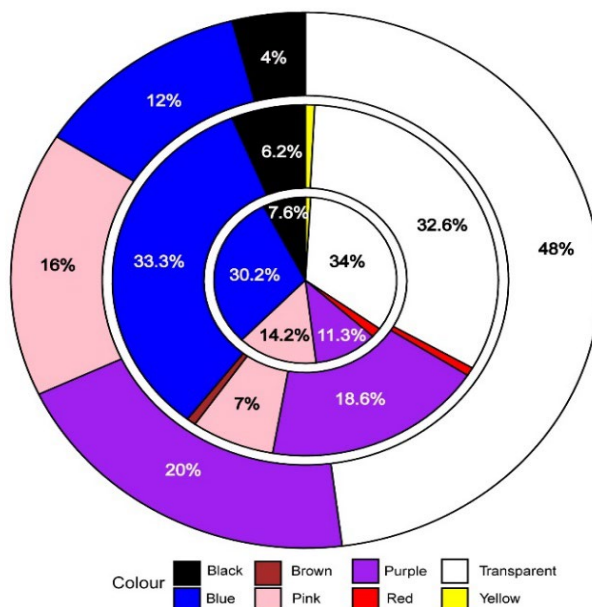


Figure 5. The distribution of microplastic colors for November, December and January (from innermost to outermost circle).

SEM Analysis

In this study, scanning electron microscopy (SEM) analysis was performed on selected fibers and pellets to examine their surface morphology, providing insights into their behavior in the atmosphere. Different MP types exhibited distinct morphological features on their surfaces. Figure 6a shows a pellet MP with flakes and adhering particles. These adhering particles on the pellet surface represent unidentified atmospheric particulates deposited during transport, consistent with observations reported by Chenappan et al. (2024). Meanwhile, Figures 6b and 6c show the deep cracks and fractures formed in the fiber structure, respectively. Considering that airborne MPs can remain suspended for several days, these particles undergo prolonged exposure to UV radiation, oxidation processes and mechanical weathering. These processes markedly alter the surface properties of MPs, resulting in morphological changes such as fragmentation, fissuring and increased surface roughness (Liu et

al., 2019; Song et al., 2017). The large surface area-to-volume ratio of weathered MPs also makes them effective sorbents for toxic chemicals, including heavy metals and organic pollutants, allowing them to act as carriers of contaminants (Tan et al., 2021). This surface characteristic has important implications for the transport and deposition of chemical pollutants in the environment. However, this study did not examine the presence of elemental adsorption on the MP surfaces, which needs further validation. While the health impacts of MPs are not yet fully understood, airborne MPs bound to pollutants may increase the risk of respiratory disease in humans through inhalation (Gasperi et al., 2018; Vianello et al., 2019).

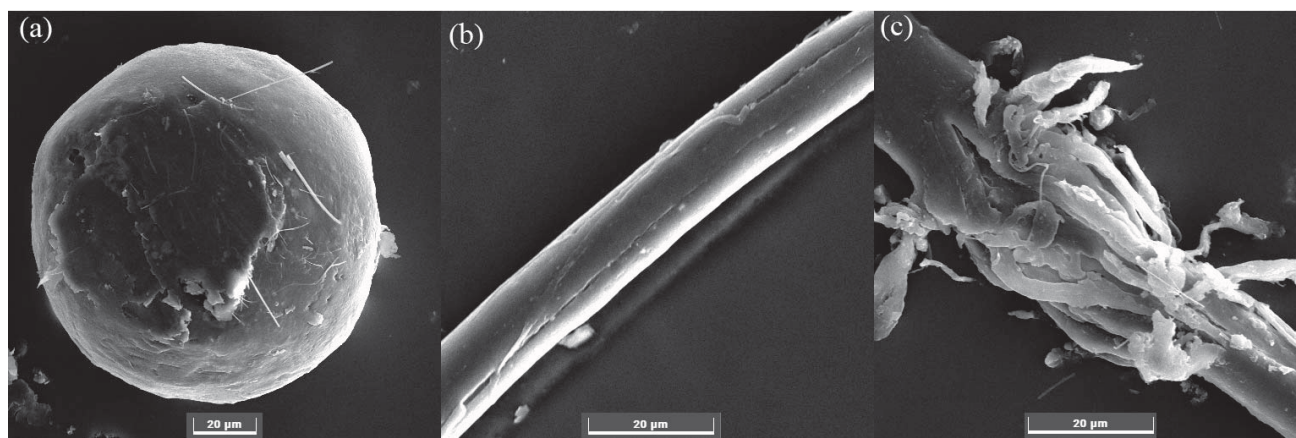


Figure 6. SEM images of environmental weathering features, (a) flakes and adhering particles, (b) deep cracks and (c) fractures.

4. Conclusion

The characteristics of airborne MPs, including abundance, particle shape, color and surface morphology, were investigated in the present study. The results confirmed the presence of microplastic particles in every deposition sample collected from a coastal area of Kuala Nerus, with the deposition rate of particles ranging from 18.32 to 372.41 MP/m²/d. The predominant MP type observed in the deposition samples was transparent fibers. As expected, their physical properties allow fibers to remain airborne and travel considerable distances from their source. In Kuala Nerus, potential local sources such as fishing activities, coastal tourism and waste disposal methods (e.g., open burning and open dumping) may contribute to the release of synthetic fibers into the surrounding environment. In addition, mechanical disturbance of beach sediments and plastic debris, particularly under monsoonal winds, may promote secondary resuspension of MPs into the air column. The local climate of Kuala Nerus during the Northeast Monsoon (November–March) is characterized by strong northeasterly winds and heavy rainfall, which may further influence MP transport and deposition rates. Therefore, measurement of meteorological parameters such as wind speed, wind direction, relative humidity, ambient temperature and rainfall would provide a more comprehensive understanding of MP deposition dynamics. Moreover, the collection of samples across monsoonal seasons would allow direct comparison of input fluxes between wet and dry periods.

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