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Spatiotemporal dynamics of microplastic contamination in the volcanic Lake Toba, Indonesia

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ABSTRACT

Lake Toba, located in the Bukit Barisan Mountain range, is the largest volcanic lake in Southeast Asia and the world. It was formed by an ancient supervolcanic eruption approximately 75,000 years ago. The lake is surrounded by densely populated areas and fed by 289 inflowing rivers, making it highly vulnerable to microplastic contamination from various anthropogenic sources. Water and sediment samples were collected across 15 water stations and 4 sediment stations, positioned based on a preliminary macroplastic assessment using Sentinel-2 remote sensing analysis. However, information regarding the presence of microplastics in volcanic lake environments remains limited. Water sampling was conducted using a plankton net, while sediment samples were collected using a sediment trap, followed by drying and observation under a stereo microscope; polymer identification was performed using Fourier transform infrared (FTIR) spectroscopy. The results revealed that the dominant microplastic shape in the lake water was pellets, characterized by a yellow coloration and a size of < 325 μm. The highest microplastic concentration was recorded at Station 4 with 108 particles/L, whereas the lowest concentrations were observed at Stations 2 and 8 with 10 particles/L. FTIR analysis indicated that polypropylene (PP) was the most dominant polymer type (22.2%), likely originating from packaging and textile waste, while polyvinyl chloride (PVC) and cellulose acetate (CA) exhibited the lowest proportions at 3.7% each. The widespread occurrence of microplastics demonstrates a significant anthropogenic impact on the aquatic ecosystem of Lake Toba and highlights potential ecological risks to aquatic organisms and surrounding communities. These findings provide critical baseline scientific data for environmental monitoring, sustainable lake management, and the development of mitigation strategies for microplastic pollution in the Bukit Barisan region.

Keywords: microplastics, Lake Toba, water, sediment, polymer types.

INTRODUCTION

Plastic pollution has emerged as a pressing environmental issue of the 21st century due to poor waste management (Eerkes-Medrano and Thompson, 2018). With only a small fraction recycled, most generated plastic waste accumulates in ecosystems. If current production trends continue unchecked, it is estimated that roughly 12,000 million metric tons of plastic waste will clog global landfills and the natural environment by 2050 (Geyer et al., 2017; Haram et al., 2020), sector produces more than 280 million metric tons of plastic garbage per year (Bexeitova et al., 2024). Concurrently, the accumulation of synthetic debris in natural ecosystems is considered 'poorly reversible' because native mineralization processes are exceptionally slow, while engineered remediation solutions remain highly improbable (MacLeod et al., 2021). This critical contamination threat is particularly evident in vulnerable lacustrine systems, where rising anthropogenic pressures accelerate microplastic distribution across water columns, zooplankton communities, and higher trophic levels (Dris et al., 2017; Jiménez-Contreras et al., 2024). While global attention has primarily focused on the accumulation of plastics in the oceans, freshwater ecosystems particularly lakes also face serious threats from these pollutants. One of the most concerning forms of contamination is microplastics, plastic particles smaller than 5 mm (Scheurer and Bigalke, 2018; Rochman and Hoellein, 2020; Vethaak and Legler, 2021; Azhar an Khalid, 2026), which originate either from the fragmentation of larger macroplastics or directly from consumer products (Thompson et al., 2004; Li et al., 2018; Golwala et al., 2021). Growing apprehensions surround microplastic pollution due to its detrimental impacts on both aquatic ecosystems and human health. Beyond their persistence as physical debris, these particles act as vectors for the dispersion of chemical micropollutants through continuous adsorption processes. Within aquatic environments, the pathways of these contaminants are highly diverse, originating from land runoff, industrial activities, effluents from wastewater treatment plants, atmospheric deposition, and improper waste disposal (Sun et al., 2019; Birch et al., 2020).

The past decade, research on microplastics has been predominantly centered on marine ecosystems, whereas studies on freshwater systems, especially in tropical regions, remain relatively limited (Free et al., 2014; Koelmans et al., 2019; Chen et al., 2024a). This gap persists despite the fact that freshwater environments face intense pressure from various terrestrial and anthropogenic sources. The pathways and sources of microplastics in these aquatic environments are highly diverse, spanning land runoff, industrial activities, effluents from wastewater treatment plants, atmospheric deposition, and improper waste disposal (Golwala et al., 2021). Once these synthetic particles enter lentic systems, their transport, accumulation, and ultimate fate become highly complex. Recent studies indicate that human activities, hydrological conditions, and local environmental factors strongly influence the distribution of microplastics in lakes (Cera et al., 2022; Li et al., 2018). In deep lake environments, these physical and anthropogenic drivers do not merely dictate the spatial patterns of the debris across the water column but also control its deposition and long-term storage within benthic zones. Consequently, understanding the spatiotemporal dynamics of these contaminants in both the pelagic and sedimentary matrices is critical to evaluating their overall ecological risks (Chen et al., 2024b). As semi-enclosed water bodies, lakes function as sinks for pollutants transported from their catchment areas. This characteristic makes lakes particularly vulnerable to the accumulation of microplastics originating from various sources, such as stormwater runoff, domestic and industrial effluents, and atmospheric deposition (Tang et al., 2022; Akdemir et al., 2025). The presence of microplastics in lakes poses not only a threat to biodiversity but also potential health risks to humans, as many lakes serve as sources of raw water for domestic consumption (Jolaosho, 2025; Ali, 2024). Field studies have revealed that microplastic contamination in lakes is a global phenomenon.

A survey of 48 shallow tropical lakes in Latin America reported that all sediment samples contained microplastics, with fibers being the dominant form, accounting for 76% (Jiménez-Contreras et al., 2024). Similar results were found in Mexico, where microplastics were detected not only in the water column but also in zooplankton and fish, suggesting potential disruptions to aquatic food webs (Malla-Pradhan et al., 2022). Even in remote lakes such as Lake Cadagno in Switzerland, recent studies have identified significant microplastic accumulation in sediments, underscoring that even minimally disturbed freshwater ecosystems remain vulnerable to this contaminant (Abel et al., 2025; Akdemir et al., 2025).

In Indonesia, research on microplastics has gradually expanded, particularly in coastal and riverine environments. However, studies specifically addressing microplastic contamination in large lakes remain scarce. The world's largest caldera or volcano crater is that of Toba, north-central Sumatra, Indonesia, covering 1.775 km (685 miles). It last erupted around 75,000 years ago (Chesner, 2025). Lake Toba, a volcanic freshwater lake within a complex hydrological network, holds strategic ecological and socioeconomic importancenot only as an aquatic ecosystem but also as a source of livelihood for local communities through tourism, fisheries, and water supply. Domestic, tourism-related, and fishing activities in the region likely contribute significantly to microplastic input into the lake. According to data (KLH, 2011), Lake Toba has 289 inflowing rivers, consisting of 112 rivers from Samosir Island and 117 from other water catchment areas. Among these 289 rivers, 57 are perennial, while the remaining 222 are intermittent (seasonal).

MATERIALS AND METHODS

Study site and period

The study was conducted in Lake Toba, North Sumatra, Indonesia, located at coordinates 2°21′–2°53′ N and 98°31′–99°06′ E. Administratively, the Lake Toba region encompasses 490 villages across 35 districts distributed among the regencies of Toba, North Tapanuli, Dairi, Karo, Simalungun, Samosir, and Humbang Hasundutan (BPS-Statistics Indonesia, 2025). Sampling was carried out during the dry season. Water and sediment sampling was carried out in different sectors of the lake (northern, eastern, southern, western) using a plankton net and a sediment trap sampler, respectively (Cera et al., 2022; Rahmatsyah et al., 2026). To optimize the field sampling of microplastics, potential macroplastic accumulation zones were initially identified by detecting floating material patches on the lake surface. These features were highlighted using the novel floating debris index (FDI) computed from the Sentinel-2 multi-spectral instrument (MSI) data (Figure 1) (Biermann et al., 2020; Cerra et al., 2025).

Sampling design and station selection

Water samples were collected from 15 stations (Table 1), while sediment samples were

Table 1. Research location of water sampling in the Lake Toba

Station	Sample name	Position	
		Latitude	Longitude
1	Lake Water	2.688511	98.923734
2	Lake Water	2.679182	98.831624
3	Lake Water	2.653017	98.862651
4	Lake Water	2.536477	99.005203
5	Lake Water	2.537107	99.008149
6	Lake Water	2.552664	98.988895
7	Lake Water	2.665921	98.931834
8	Lake Water	2.33737	99.062543
9	Lake Water	2.445083	98857712
10	Lake Water	2.348128	99.075356
11	Lake Water	2.897884	98.530541
12	Lake Water	2.896617	98.528350
13	Lake Water	2.855608	98.524431
14	Lake Water	2.824406	98.527474
15	Lake Water	2.791555	98.532011

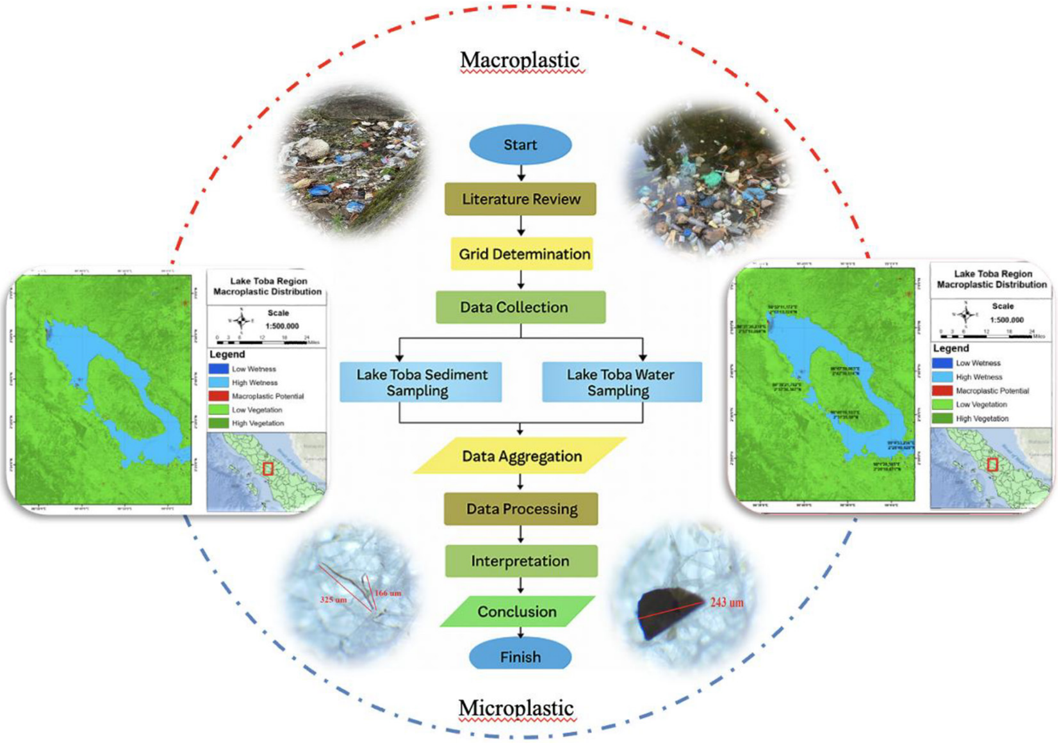

Figure 1. Research flow chart based on preliminary macroplastic mapping using Sentinel-2

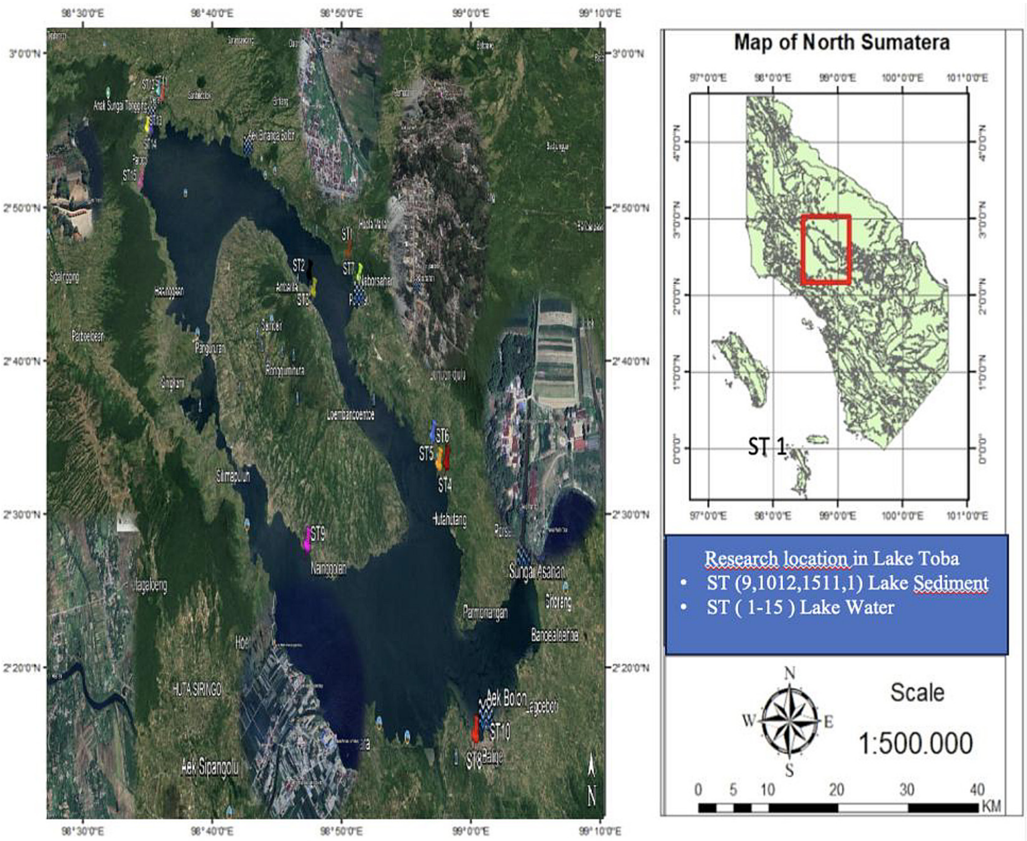

Figure 2. Sample collection locations, where green dots represented water samples and red dots represented sediment samples

obtained from 4 stations (Figure 2 and Table 2). A purposive sampling method was employed to represent variations in anthropogenic pressures (residential, tourism, and fisheries), proximity to river mouths, and distinct aquatic characteristics. The limited number of sediment stations compared to water stations was due to the focus on primary depositional zones and particle accumulation areas, which are considered representative for microplastic evaluation in sediments.

Water and sediment sampling procedures

Water samples were collected using a plankton net at designated depths. The filtered samples were then transferred into sterile glass bottles and kept sealed until laboratory analysis. Sediment samples were retrieved using sediment traps deployed on the lake bed. Once collected, the sediment was oven-dried at 60 °C for 24 hours and stored in sterile containers for further processing (Masura et al., 2015; Rahmatsyah et al., 2024).

Table 2. Research location of sediment sampling in the Lake Toba

Station	Sample name	Position	
		Latitude	Longitude
1	Sediment 1	2.348128	99.075356
2	Sediment 2	2.445083	98857712
3	Sediment 3	2.791555	98.532011
4	Sediment 4	2.896617	98.528350

Laboratory processing and density separation

Both water and sediment samples were processed in the laboratory. Microplastic separation was achieved through density separation using KOH and saturated NaCl solutions. Microplastic particles with lower density floated to the surface and were subsequently filtered using Whatman No. 41 filter paper (Masura et al., 2015; Rahmatsyah et al., 2026).

Morphological identification and polymer characterization

Morphological identification of microplastics, categorized as fibers, films, fragments, pellets, and foam, was performed using a stereo microscope (Masura et al., 2015; Chandra and Walsh, 2024). Finally, polymer characterization was conducted via Fourier transform infrared spectroscopy (FTIR) to identify the functional groups and specific polymer types of the microplastics (Li et al., 2018; Falahudin et al., 2020).

RESULTS AND DISCUSSION

Population

Based on data from the Central Bureau of Statistics (BPS) for the period 2021–2025, the total population of the seven regencies within the Lake Toba Region increased from 2,585,860 to 2,740,660 inhabitants an increase of 154,800 people or approximately 6.0% over five years, with an average annual growth rate of about 1.46%. The population growth trend was monotonic across all regencies. Simalungun Regency contributed the largest absolute increase, rising from 1,003,727 to 1,067,499 inhabitants an addition of 63,772 people followed by Dairi Regency (+24,738) and Karo Regency (+22,972). In terms of relative growth rate, Dairi Regency recorded the highest rate (≈ 1.93% per year), followed by Simalungun (≈ 1.55%/year) and Karo (≈ 1.38%/year). The smaller-populated regencies Toba, Samosir, North Tapanuli, and Humbang Hasundutan exhibited relatively stable growth rates, ranging between 1.20 –1.27% per year (Figure 3). Overall, these figures indicate a uniform population growth across the Lake Toba region, with implications for the increasing demand for infrastructure, resources, and waste management systems to support sustainable regional development.

Population growth in the lake's coastal area during the 2021–2025 period, which is projected to increase by around 6%, has direct implications for plastic waste and other anthropogenic residues. Population growth is usually correlated with increased consumption of disposable products, mobilization of textile fibers (Ballent et al., 2016) from household activities, and increased domestic and commercial effluent loads (Li et al., 2018). These anthropogenic sources enter the hydrological system through surface runoff, drainage channels, and direct discharge into water bodies observed at station 14, which is an area of residential settlements, port docks, tourism, and river flow. In the context of Lake Toba, the hydrological network consisting of ±289 tributaries functions as a "conveyor belt" that transports plastic particles, microplastics, and other pollutants from the catchment area to the water column and sediments of Lake Toba. Seasonally variable river discharge, ranging from 41.6 to 124.9 m³/sec, reinforces the "collect-and-concentrate" mechanism, whereby pollutants dispersed upstream are collected in the lake system. The intensity of this process increases during the rainy

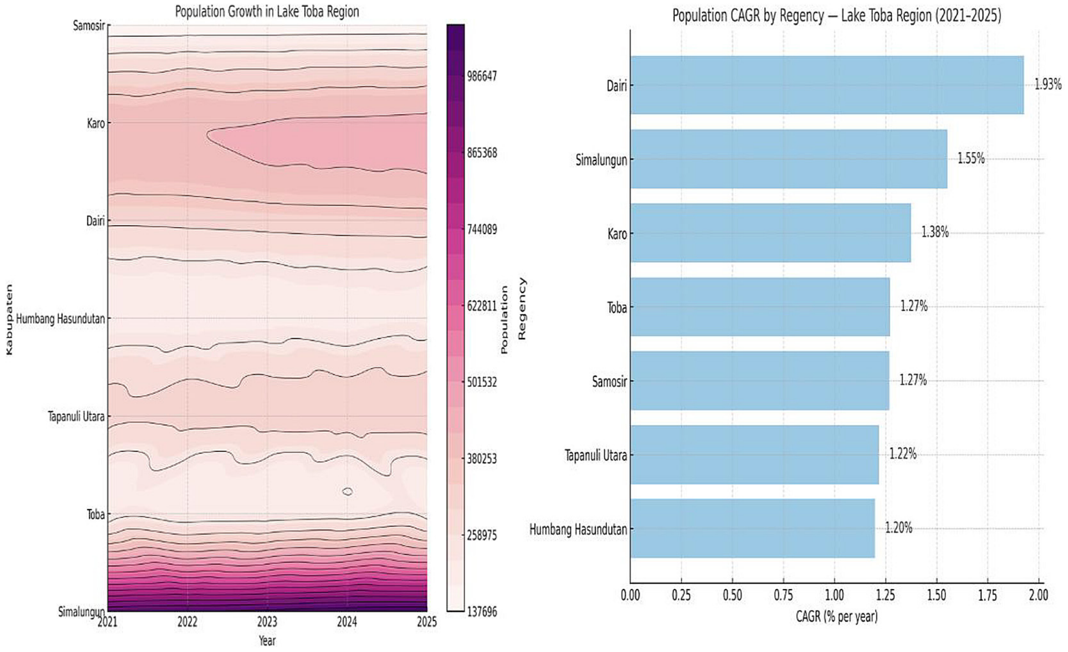

Figure 3. Population in the regencies of Lake Toba

season because rainfall increases flushing and surface erosion, thereby driving larger amounts of macro and microplastics into the water body (Tang et al., 2022). In addition to natural factors, local anthropogenic dynamics exacerbate pollutant contributions. Dense settlement activities on the shores, household laundries that release synthetic fibers, workshops and motorboats that contribute technical plastic residues, and tourist markets that produce disposable packaging are significant potential sources. Recent research shows that microplastic hotspots in lakes and rivers are often associated with areas of intensive human activity, and that hydrological structures play an important role in determining their spatial distribution (Li et al., 2018; Nava et al., 2023). These findings confirm that mitigation strategies need to focus on upstream control, including strengthening residential waste management, installing trash traps at river mouths, and regulating tourism and water transportation activities. Such interventions are in line with recommendations

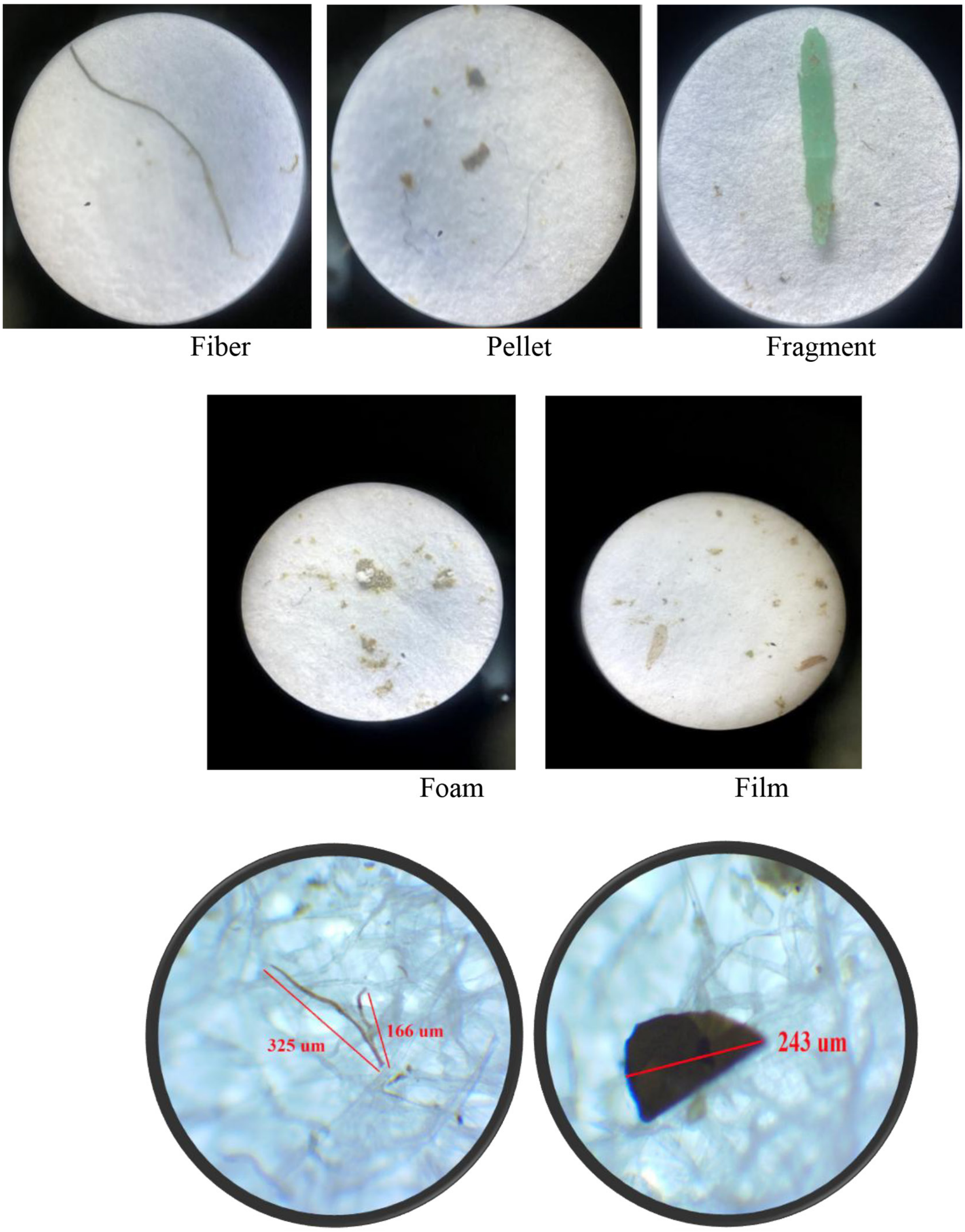

Figure 4. Types and sizes of microplastics from water and sediment samples

(Bexeitova et al., 2024; Tang et al., 2022), which highlight the effectiveness of integrating watershed-based management in reducing plastic pollutant flows into lake systems. Thus, combining an understanding of anthropogenic and hydrological dynamics is key to designing sustainable management policies for Lake Toba. Through an integrated approach that includes reducing plastic sources upstream, effective waste management, monitoring hotspots, and increasing community and tourism awareness and participation. Consistent implementation of this strategy is expected to minimize microplastic accumulation, maintain water ecosystem quality, and support environmental sustainability and the health of communities around Lake Toba.

Type of microplastic

Observations using a stereo microscope conducted on lake water samples from 15 sampling stations and four bottom sediment samples revealed the presence of five types of microplastic particles, namely fibers, fragments, pellets, films, and foams, as shown in Figure 4. This study also revealed that pellets were the most dominant microplastic found in Lake Toba (Figure 5).

The amount of microplastics detected at each sampling station varied depending on environmental conditions, land use, and community habits near the lake and its tributary rivers (Figure 6). According to Zhang et al., (2018), there is a strong correlation between improper plastic waste disposal behavior and the abundance of microplastics in aquatic environments. The growing population and increasing human activities generate significant quantities of organic, inorganic, and industrial waste. Plastic waste originating from terrestrial areas can be transported into rivers via rainwater runoff or drainage systems. Moreover, plastic waste that is intentionally dumped into rivers further contributes to the rise in microplastic concentrations. The variation in shape, color, and abundance of microplastics found in lake water depends on the source and type of degraded plastic. The distribution of microplastics within the lake is highly heterogeneous, influenced by location, human activity, and local environmental conditions such as water currents and sedimentation rates. Chen et al. (2024c) emphasized that microplastic pollution tends to increase in areas with high anthropogenic activity (Grbić et al., 2020). Based on particle morphology, the most abundant type of microplastic identified across the 15 sampling stations was pellets, totaling 411 particles. These originate mainly from industrial plastic waste and microbeads used in raw plastic materials, toiletries, soaps, and facial cleansers. Fibers, totaling 289 particles were the second most common form. These fine, thread-like particles of varying colors are easily suspended in water. They typically derive from degraded fishing gear such as ropes and nets, as well as laundry activities, where washing synthetic fabrics can

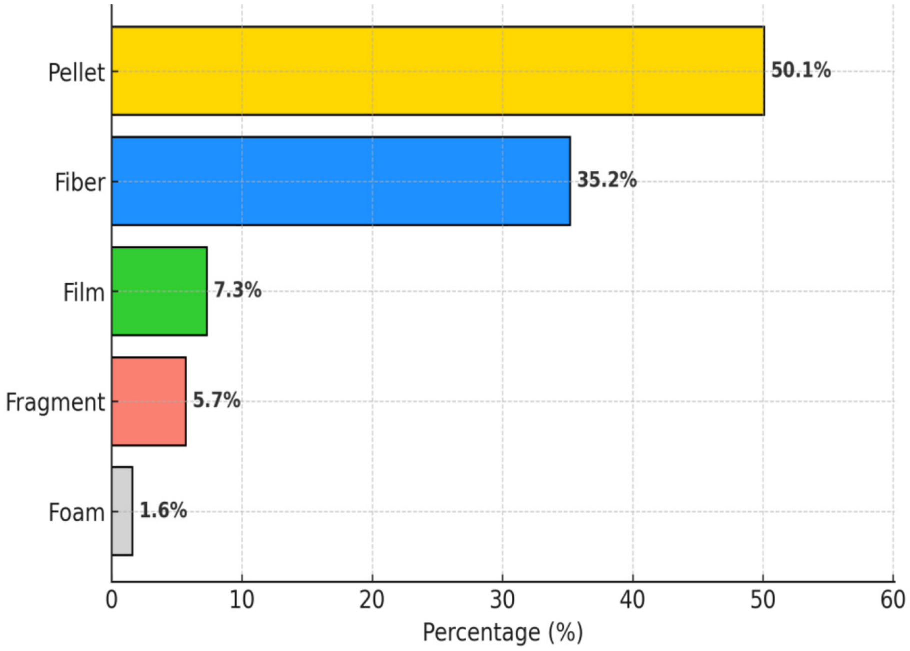

Figure 5. Percentage of microplastic types in the water samples from Lake Toba

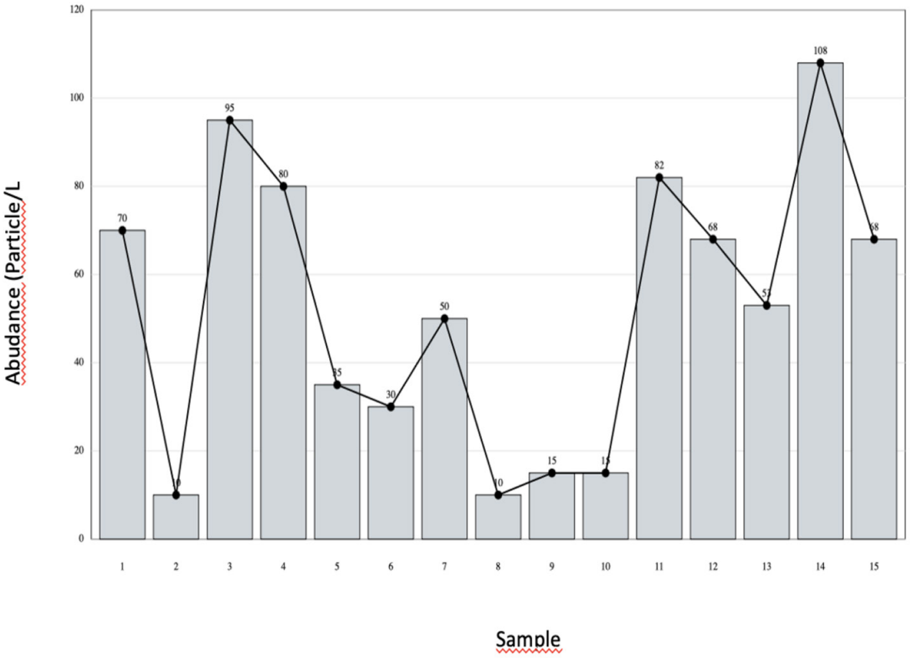

Figure 6. Abundance of microplastic from water samples

release up to 2 grams of fibers per wash cycle. Microplastic fibers were particularly abundant near residential areas where laundry and fishing are common activities (Abel et al., 2025; Mahidev, 2024). The third most common type was film-shaped microplastics (60 particles), characterized by thin, flexible, and transparent sheets. These particles result from the degradation of plastic bags, food wrappers, and product packaging, which break down easily due to their low density. Fragments ranked fourth (47 particles), consisting of irregular, angular pieces derived from plastic bottles, PVC pipes, food packaging, boat paint, and other household plastic products discarded near the lake. These fragments generally have low density, allowing them to float on the lake surface. The least abundant type was foam microplastics, with only 13 particles observed. The white color of these particles likely originates from polystyrene foam containers and plastic bags discarded around the lake, suggesting prolonged photodegradation by UV radiation. The findings indicate that two main categories of microplastics are present in Lake Toba: Primary microplastics, directly manufactured as microscopic particles for commercial products such as fishing nets and cosmetics. Their presence in the environment primarily originates from domestic wastewater, river runoff, atmospheric deposition, and local community activities around the lake. Secondary microplastics, produced from the degradation of larger plastic debris scattered in the environment. These plastics release microscopic particles through weathering processes driven by UV radiation, physical abrasion, and strong winds, leading to the widespread dispersal of microplastics within the lake ecosystem.

The spatial distribution of microplastic particle abundance (particles/L) across the 15 sampling stations (ST1–ST15) was analyzed and visualized using a contour map generated through bilinear interpolation, which effectively illustrates the gradient variations between stations. The highest abundance was recorded at Station 14 (108 particles/L), indicating a hotspot of particle accumulation, while the lowest concentrations were observed at Station 2 (10 particles/L) and its surrounding areas. This spatial heterogeneity suggests that hydrodynamic conditions and anthropogenic inputs play significant roles in determining the distribution patterns of microplastic particles within the study area. The variation in microplastic abundance among stations is closely related to environmental conditions, land-use patterns, and human activities near the lake and along the rivers that flow into it. According to Zhang et al. (2018), there is a strong correlation between public waste disposal behavior and microplastic abundance in aquatic systems. The dense population and extensive human activities around the lake contribute to the generation of organic, inorganic, and industrial waste. Plastic debris from land areas can be transported into river bodies through rainwater runoff or drainage systems, while direct disposal of plastic waste into rivers further increases microplastic concentrations. The variations in shape, color, and abundance of microplastics accumulated in the lake depend on the source material and the degree of degradation of the original plastics. The contour map showing the distribution pattern of microplastics across the 15 sampling stations (as presented in Figure 7) provides a clear representation of the differences in both quantity and form of microplastics detected in Lake Toba's water. The main purpose of constructing this spatial distribution map supported by the legend and highlighted areas is to visualize the spatial variation of microplastic types and to indicate specific locations where sediment and water sampling were conducted within the Lake Toba region.

Lake Toba acts as a microplastic "sink," a common feature of semi-enclosed water bodies with relatively weak currents and long water residence times. Globally, critical studies show that lakes and freshwater drinking water sources store microplastics from various sources (runoff, domestic/industrial effluent, and atmospheric deposition), with common morphotypes being fibers, fragments/films, and lightweight polymers such as PP/PE/PS. This pattern is consistent with data from Lake Toba, where particles are distributed across all stations and show an accumulation hotspot (ST14) of 108 particles/L. The literature also notes peaks in abundance near river mouths/zones of anthropogenic activity relevant for Lake Toba given the presence of 289 tributaries and seasonally fluctuating inflows (41.6–124.9 m³/s) (Koelmans et al., 2019; Tang et al., 2022; Jiménez-Contreras et al., 2024).

Field data from Lake Toba shows that microplastics in sediments and water columns are dominated by pellets and fibers, followed by films, fragments, and foam. The dominance of pellets is generally associated with resin pellets, which are raw materials for the plastics industry, as well as microbeads from cosmetic products, which are easily mobilized into waterways through domestic and industrial waste disposal (Driedger et al., 2015; Su et al., 2016; Koelmans et al., 2019; González-Pleiter et al., 2020). Meanwhile, fibers originate mainly from fishing and textile activities; nylon or PE fishing nets or lines, and the release of synthetic fibers during household washing are the main contributors. The color distribution of microplastics provides additional information about the source and degree of weathering. Color fading or darkening due to ultraviolet radiation, biofouling, or chemical degradation can alter the visual spectrum of particles, so color can

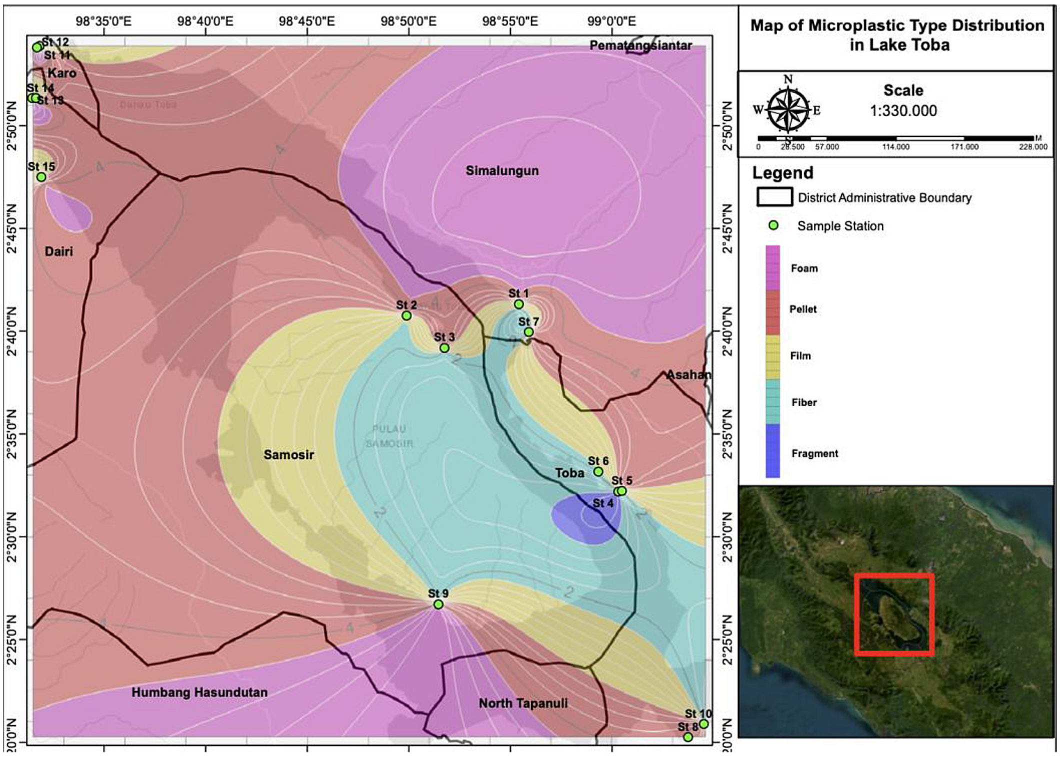

Figure 7. Contour of microplastic distribution patterns in the Lake Toba

be used as an indicator of degradation processes and particle travel in the environment (Tang et al., 2022; Jiménez-Contrera et al., 2024). These results are consistent with observations in other tropical lakes, such as in Mexico, where fibers and fragments dominate and have been shown to undergo trophic transfer to aquatic organisms, emphasizing the importance of ecological risk assessment and fisheries impacts (Koelmans et al., 2019; Boateng et al., 2024). Thus, the morphology and physical characteristics of microplastics in Lake Toba not only reflect different anthropogenic sources but also provide insights into the dynamics of distribution, degradation, and potential accumulation in tropical freshwater ecosystems.

The distribution of microplastics in the study area shows striking spatial heterogeneity, with the highest concentrations at Station 14 and the lowest at Stations 2 and 8. This pattern confirms the complex interaction between anthropogenic pressures, including settlements, tourism activities, and fishing and local hydrodynamic factors, such as coastal currents, water depth, and bay morphology. These findings are consistent with the study by Tang et al. (2022) in Songshan Lake, China, which reported significant variations between lake segments and differences in microplastic distribution between surface water and sediments. These results highlight the urgency of location-based hotspot mapping and the implementation of targeted management interventions to mitigate microplastic accumulation, while supporting more effective and sustainable aquatic ecosystem management.

Color of microplastics

The colors of microplastics found in the waters of Lake Toba varied and included yellow, black, blue, red, transparent, white, and green. The dominant color observed was yellow (47.4%), followed by black (20.5%), blue (10.2%) (Chen et al., 2024), red (9.9%), transparent (9.8%), and both white and green (1,1%) (Figure 8). The variation in microplastic color is primarily influenced by source origin, degradation processes, and environmental interactions. Studies have shown that the color of microplastics can also serve as an indicator of pollution sources and distribution patterns within an aquatic system (Figure 9). Ultraviolet (UV) exposure can induce color changes in plastics, ither fading or darkening, depending on the type of polymer and pigment additives used in the material. Moreover, aquatic organisms often mistakenly ingest microplastics due to their similarity in color, shape, and size to natural food particles, posing potential risks to aquatic food webs and ecosystem health.

FTIR measurement

The FTIR wave measurements found in the sediment samples from Lake Toba. The functional groups and types of plastic polymers can be identified by comparing the position of the wave absorption values using references in the ATR-FTIR Library. The results of the analysis of the functional groups and types of polymers

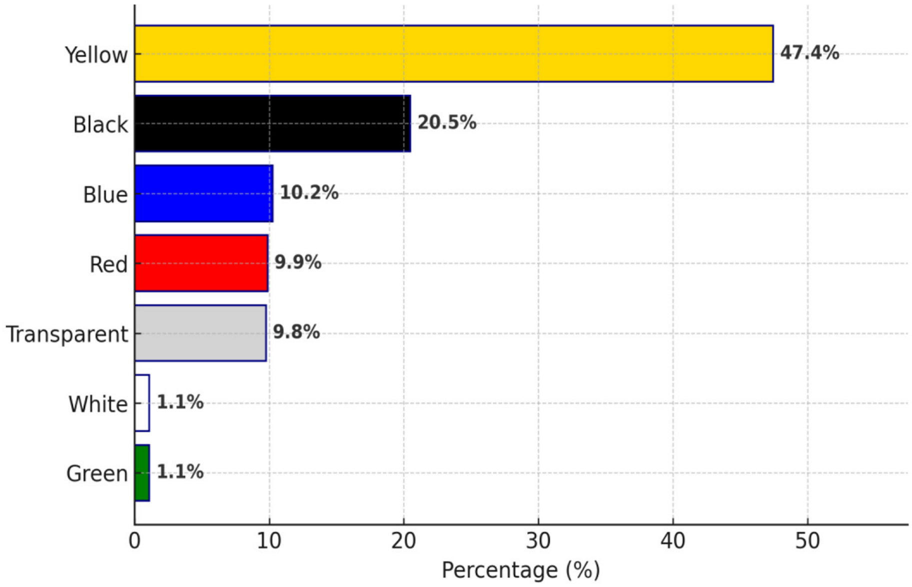

Figure 8. Distribution (%) of colors of microplastic types in the water samples from Lake Toba

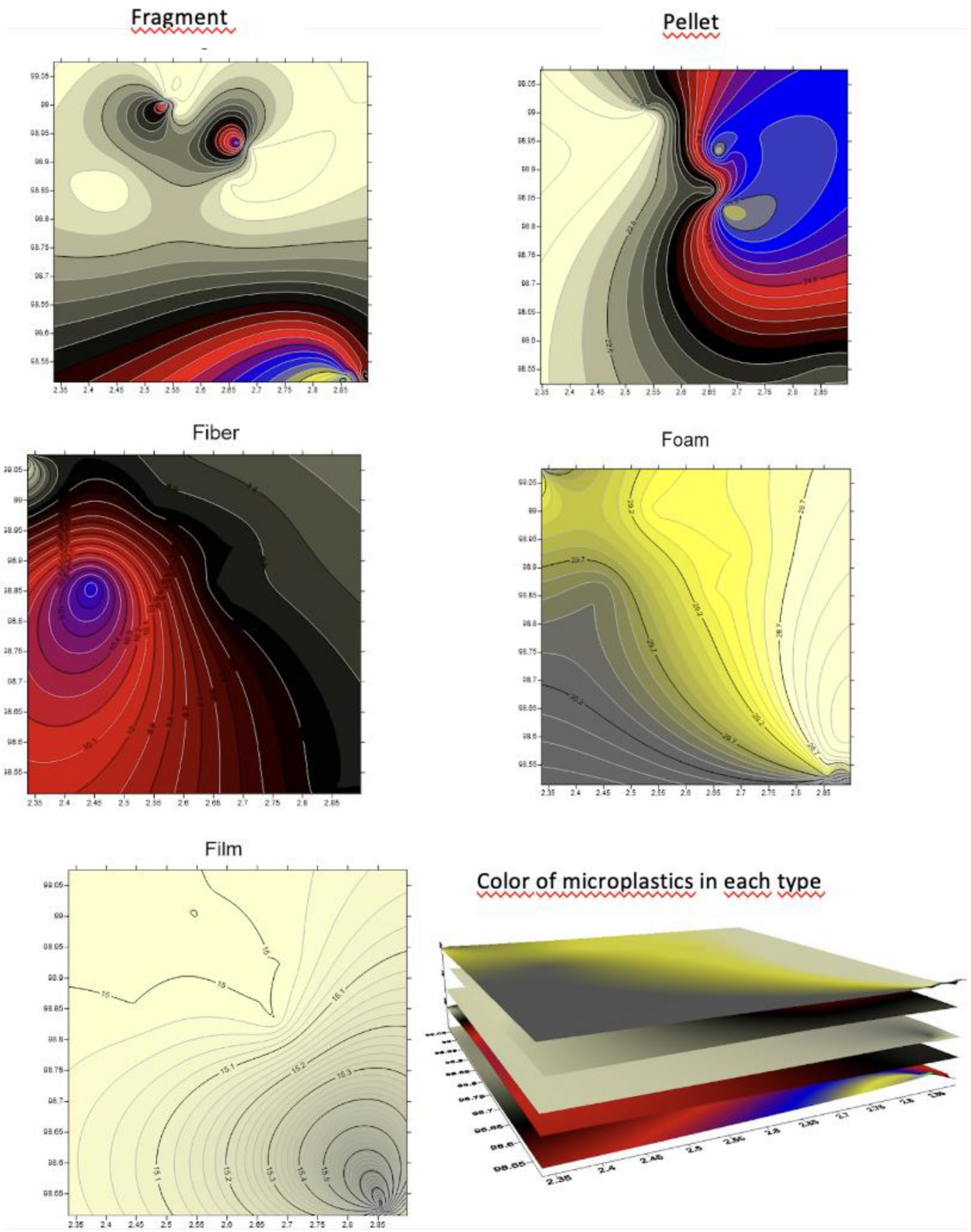

Figure 9. Color contours of microplastic types at each station in the water samples from Lake Toba

contained are shown in Figure 10. Based on the results of microplastic research in sediment FTIR testing (Boateng et al., 2024), the wavelength in the FTIR test identified four types of polymers, the most commonly found being polypropylene (PP) polystyrene (PS), and polytetrafluoroethylene (PTFE) (Chen et al., 2024c). Polypropylene (PP) was detected at absorption peaks of 992.30 cm^{-1} and 776.66 cm^{-1}, which have C-C stretching and CH_2 rocking bonds (Veerasingam et al., 2021). In the FTIR test of sediment 2, the wavelengths in the FTIR test identified the five most common polymers found: polypropylene (PP), polytetrafluoroethylene (PTFE), polyethylene terephthalate (PET) (Deng et al., 2020) and polyvinyl chloride (PVC). Polypropylene (PP) was detected at absorption peaks of 991.59 cm^{-1} and 778.76 cm^{-1}, which have C-C stretching and CH_2

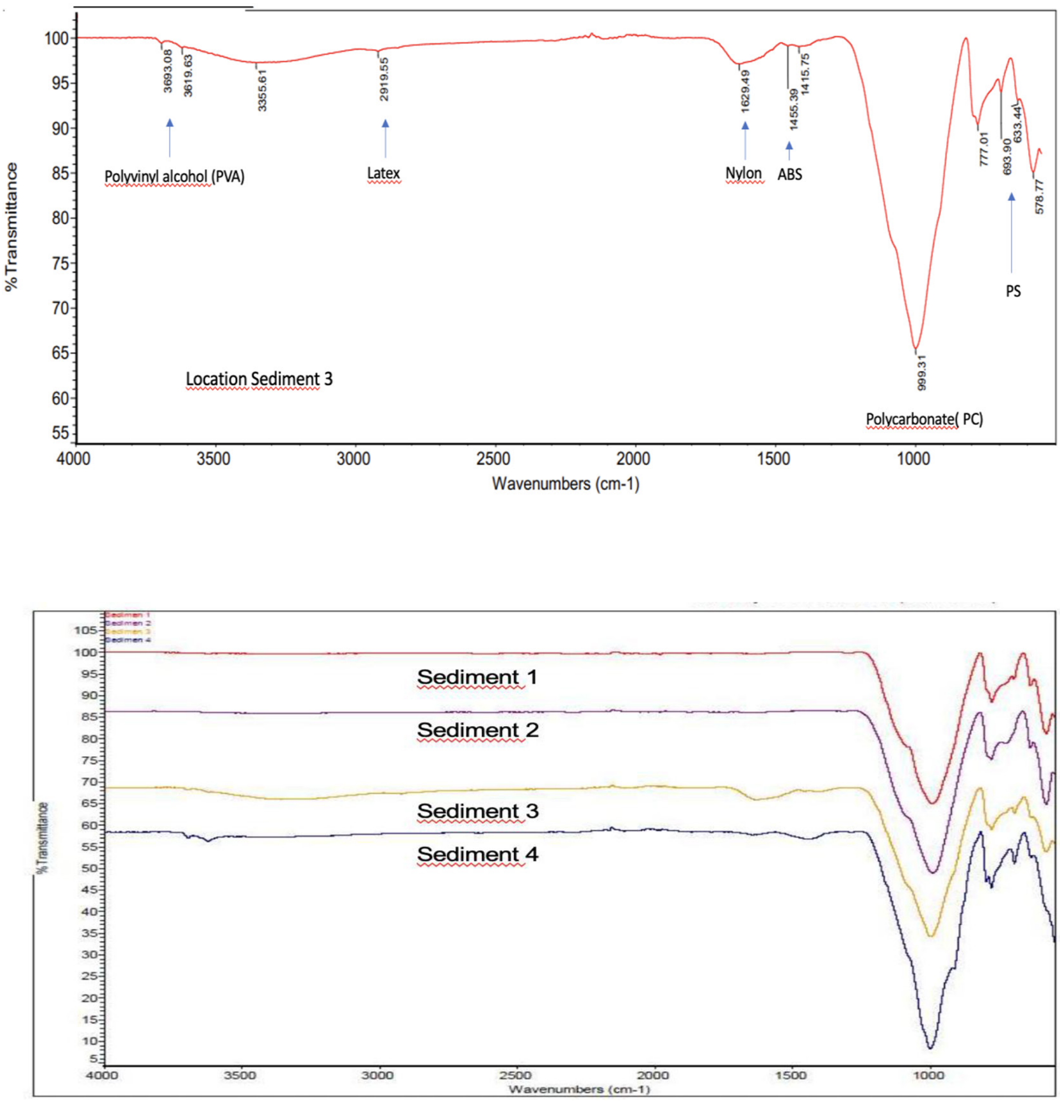

Figure 10. FTIR results for sediments 1-4 from Lake Toba

rocking bonds. Polyvinyl chloride (PVC) was detected at an absorption peak of 578.42 cm^{-1}. The microplastic form in PVC polymers is fragment. In the FTIR test of sediment 3, wavelength analysis in the FTIR test identified 10 types of polymers, the most commonly found being polyvinyl alcohol (PVA), latex, nylon (all polyamides), Acrylonitrile butadiene styrene (ABS), Polycarbonate (PC), LDPE, Polystyrene (PS), Polytetrafluorethylene (PTFE), and Polypropylene (PP). Nylon was detected at the peak absorption wavelength of 1629.49 cm-1. Nylon is a type of synthetic polymer commonly used in fishing equipment such as nets, ropes, fishing lines, and other fishing gear that can degrade into fiber-type microplastics in water (Patidar et al., 2024) (Figure 11).

Based on the results of microplastic research in the FTIR sediment test 4, wavelength analysis in the FTIR test identified 7 types of polymers (Table 3). The most common polymers found were PVA, PP, CA, EVA, PS, and PTFE. PVA was detected at absorption peaks of 3693.38 cm^{-1} and 3620.57 cm^{-1}, which have O–H stretching bonds. PVA is a water-soluble synthetic polymer that is one of the sources of film-type microplastics. PVA comes from paper coatings, tablet medicines, and other adhesive industries. Sediments 1–4 showed that PP was the dominant polymer with a percentage of 22.2%, followed by PTFE and PVA at 14.8% each, and PS at 11.1%. Meanwhile, other polymers such as PET, PVC, LDPE, PC, ABS, Nylon, Latex, EVA, and CA each contributed 3.7%. The dominance of PP indicates a significant contribution from everyday packaging plastics, while the presence of PTFE and PVA indicates the persistent involvement of industrial

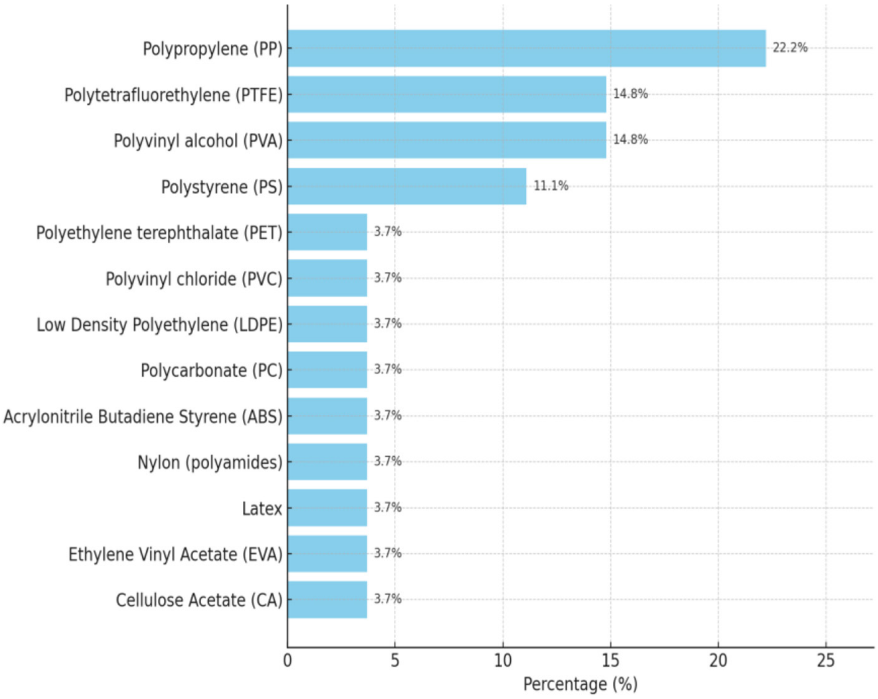

Figure 11. Polymer types in percent in the sediment samples from Lake Toba

Table 3. Microplastic polymers in the sediment samples from Lake Toba

Sample name	Wave absorption (cm^{-1})	Functional group	Type of polymer
Sediment 1	636.20	C-C-F bending	Polytetrafluorethylene (PTFE)
	695.70	Aromatic CH out-of plane bend	Polystyrene (PS)
	776.66	CH_2 *rocking*	Polypropylene (PP)
	992.30	C-C Streaching	Polypropylene (PP)
Sediment 2	578.42	C–Cl stretching	Polyvinyl chloride (PVC)
	637.20	C-C-F bending	Polytetrafluorethylene (PTFE)
	727.72	Aromatic CH out-of-plane bending	Polyethylene terephthalate (PET)
	778.76	CH_2 *rocking*	Polypropylene (PP)
	991.59	C-C Stretching	Polypropylene (PP)
Sediment 3	578.77	C-Cl Stretching	Polypropylene (pp)
	633.44	C–C–F bending	Polytetrafluorethylene (PTFE)
	693.90	Aromatic CH out-of plane bend	Polystyrene (PS)
	777.01	CH_2-Rock	LDPE
	999.31	Aromatic CH in plane bending	Polycarbonate (PC)
	1455.39	CH2 bending	Acrylonitrile butadiene styrene (ABS)
	1629.49	C=O *stretching*	Nylon (all polyamides)
	2919.55	C–H stretching	Latex
	3619.63	*O–H* stretching	Polyvinyl alcohol (PVA)
	3693.08	O–H stretching	Polyvinyl alcohol (PVA)
Sediment 4	633.94	C–C–F bending	Polytetrafluorethylene (PTFE)
	694.18	C-Cl *stretching*	Polypstyrene (PS)
	777.65	CH_2 rocking	Ethylene vinyl acetate (EVA)
	913.32	Aromatic ring Stretching	Cellulose acetate (CA)
	1454.86	C–H *stretching*	Polypropylene (PP)
	3620.57	O–H *stretching*	Polyvinyl alcohol (PVA)
	3693.38	O–H *stretching*	Polyvinyl alcohol (PVA)

polymers. Therefore, monitoring needs to focus not only on mass-consumption plastics but also on specialty polymers that have the potential to cause long-term ecological impacts.

FTIR analysis of sediment samples shows that PP is the dominant polymer with a proportion of 22.2%, followed by PTFE and PVA at 14.8% each, and PS at 11.1%. Meanwhile, other polymers such as PET (Alfonso et al., 2020), PVC, LDPE, PC, ABS, nylon, EVA, CA, and latex were only detected in minor proportions. The distribution of these polymers reflects various anthropogenic sources. The dominance of PP and PS is consistent with their widespread use in the food packaging industry, disposable containers, and various consumer products. The presence of PET and PVC indicates contributions from plastic bottles, textile fibers, and utility pipes, which are commonly found in urban and domestic environments. Meanwhile, nylon fragments are mainly associated with fishing activities, given their intensive use in nylon-6 and nylon-66-based nets and fishing gear. PVA is associated with adhesives, paper coatings, and pharmaceutical formulations, while the detection of PTFE (Teflon) indicates potential industrial or technical sources that are more persistent, such as non-stick coatings, industrial seals, and mechanical components. This composition profile is consistent with findings in various other freshwater ecosystems, where PP, PE, and PS tend to dominate the microplastic spectrum due to high global production volumes and their lightweight and degradation-resistant properties (Koelmans et al., 2019). In line with the methodological review by (Veerasingam et al., 2021), FTIR has been proven capable of identifying various polymers with high resolution, while also revealing the relationship between specific anthropogenic sources and the distribution patterns of microplastics in the environment. Thus, this analysis not only highlights the high dominance of commodity polymers such as PP and PS but also confirms the important contribution of the fisheries, industrial, and domestic sectors in shaping the microplastic profile in the sediments of Lake Toba.

Based on the contour plot in Figure 12, the sediment samples from Lake Toba show a clear disparity in the distribution of microplastic contamination, heavily dominated by Pellets and Fibers. Pellets exhibit the highest concentration, with a brilliant yellow peak indicating a maximum particle density of around 390 to 420, strongly clustered at a high particle count of 350 to over 400. Fibers follow as the second most prevalent type, showing a dense, widespread orange-pink ellipse centered around 250 to 350 particles. In stark contrast, types like Film and Foam display much lower densities, while Fragments, highlighted by the red squiggly line at the bottom left, remain almost entirely in the deep blue zone, signifying that they have the lowest density and are the least common microplastic type found in these samples.

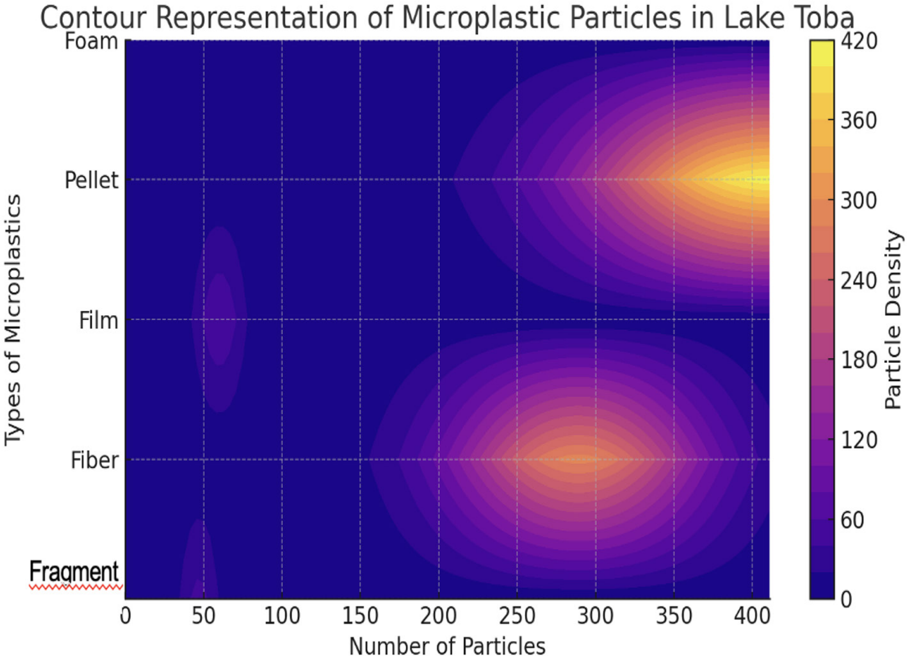

Figure 12. Number of microplastic types in the sediment samples

CONCLUSIONS

This study revealed the presence of microplastics in Lake Toba, dominated by PP, PS, and PVA polymers. A spatial survey (February–May 2025; 15 water stations, 4 sediment stations) showed microplastics at all locations, with concentrations varying from 10 particles/L to 108 particles/L, dominated by pellet and fiber morphotypes. FTIR analysis of sediments identified PP (22.2%) as the main polymer, followed by PTFE and PVA (14.8%) and PS (11.1%). Population growth in the region of 6.0% (2021–2025), particularly in Simalungun and Dairi, has the potential to increase plastic pollution. These findings confirm Lake Toba's role as a particulate pollutant sink, influenced by transport from 289 tributary rivers, seasonal discharge, and tourism and aquaculture activities. The results of this study provide an initial baseline that requires multi-season replication and strengthened QA/QC. Addressing microplastic pollution in Lake Toba requires an integrated strategy that includes waste management, wastewater treatment, multi-season monitoring, and active community participation. This approach is expected to maintain water quality, ecosystem sustainability, and reduce health risks for residents, especially at station 14, which depends on Lake Toba water.

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