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Occurrence and Water–Sediment Distribution of Suspected Microplastics in Tropical Karst Aquifers: Water–Sediment Evidence from Java Island, Indonesia

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Abstract

Contamination by suspected microplastics in karst groundwater remains poorly understood in tropical regions, although karst aquifers can rapidly transfer surface-derived particles through fractures, conduits, caves, and underground rivers. This study investigates the occurrence and water–sediment distribution of suspected microplastics (MPs) in tropical karst aquifers across Java Island, Indonesia, by examining their abundance, morphology, size, color, and polymer composition in groundwater and associated sediments and by comparing their spatial variation among karst systems with different aquifer development and human pressures. Water and sediment samples were collected from 25 springs and underground rivers across seven karst regions in Java. Samples were processed using filtration, organic matter oxidation, density separation, microscopic identification, and FTIR confirmation for selected particles. Suspected MPs were visually identified in all water samples, with abundances ranging from 26 to 78 particles/100 mL, and were also visually identified in all sediment samples, ranging from 41 to 211 particles/5 g dry sediment. Fibers dominated most groundwater samples, a pattern consistent with their potential mobility through karst flow systems, whereas sediments contained higher proportions of fragments and films, which may reflect preferential deposition and temporary accumulation within depositional zones. Spatial patterns varied with karst development, outlet type, land use, and allogenic recharge. The results suggest that MP monitoring in tropical karst should combine water and sediment sampling and be linked to waste-control measures in recharge areas to protect karst water resources.

Keywords: Java; tropical karst; karst groundwater; microplastics (MPs); sediment

1. Introduction

Microplastics (MPs) are plastic particles smaller than 5 mm that originate either from the weathering and fragmentation of larger plastic debris or from the intentional manufacture of small plastic particles for commercial applications (Bhattacharyya et al. 2022; Saeedi 2024; Cherian et al. 2024; Kumar et al. 2025). Since the 1950s, global plastic production has increased dramatically, from approximately 1.5 million tons to more than 450 million metric tons per year by 2024 (Alimba and Faggio 2019; Jung et al. 2022; Selvam et al. 2024; Nguyen et al. 2025). This rapid growth has resulted in the accumulation of an estimated 6.3 billion metric tons of plastic waste, much of which can undergo progressive fragmentation into MPs (Jung et al. 2022). These particles have now been detected in a wide range of environmental matrices, including marine ecosystems, groundwater, and terrestrial environments, as well as in human biological samples such as lung tissue, feces, placenta, and blood (Li 2018; Jung et al. 2022; Popa and Tabaran 2025). In groundwater alone, reported MPs concentrations vary widely, ranging from 0.1 to 6,832 particles per liter (Mu et al. 2022; Hoang et al. 2025; Jahan Rakib et al. 2025). Their environmental persistence, low biodegradability, and ability to disperse across multiple compartments make MPs a major global environmental concern (Murphy and Cleary 2022; Gaur et al. 2025).

Groundwater is a primary source of drinking water for nearly half of the global population (Scozzari and Dotsika 2016; Alley and Alley 2017; Khan et al. 2021). However, increasing evidence shows that groundwater can be contaminated by microplastics as a result of anthropogenic activities, particularly in areas affected by industrial development, landfills, and inadequate waste management (Mu et al. 2022; Priya et al. 2023). Owing to their polymeric structure, hydrophobicity, and surface functional groups, microplastics are highly persistent and resistant to natural degradation processes (Liu et al. 2022; Joshi 2024; Sharma et al. 2024). MPs can also adsorb other contaminants, including heavy metals and persistent organic pollutants, thereby facilitating their transport through aquatic systems and food webs, with potential adverse effects on various organisms (Liu et al.

2022; Sharma et al. 2024; Srivastava et al. 2024; Sinha et al. 2025). Human exposure to MPs may occur through contaminated food and drinking water, inhalation of airborne particles in urban and industrial environments, and direct contact with plastic-containing products or contaminated environmental media (Emenike et al. 2023; Mondal et al. 2024; Tang et al. 2024; Mumtaz et al. 2025; Nguyen et al. 2025; Visileanu et al. 2025). These exposure pathways raise growing concern about the potential long-term health implications of microplastic contamination (Yang et al. 2022; Preda et al. 2024).

Studies on microplastics have been conducted far more extensively in surface water systems, such as rivers and oceans, than in groundwater (Veerasingam et al. 2022; Yang et al. 2022; Alvarado-Zambrano et al. 2023; Sangkham et al. 2023; Hartini et al. 2024; Jahan Rakib et al. 2025). This research imbalance partly reflects the long-standing assumption that aquifers can attenuate contaminants through filtration and retention processes as water passes through vegetation, soil, and the unsaturated zone before reaching the saturated zone. These processes may slow contaminant migration and promote physical, chemical, and biological attenuation (Marín-Angel et al. 2023). However, the detection of microplastics in groundwater challenges this assumption, indicating that plastic particles can bypass or overcome natural filtering barriers and enter aquifer systems. This emerging evidence highlights the need for further research on the occurrence, transport pathways, and environmental management implications of microplastic pollution in groundwater.

Karst aquifer systems are characterized by open hydrological systems with high vulnerability to surface pollution (Balestra et al. 2023a; Shu et al. 2023). The hydrological characteristics of karst, including underground rivers, fracture networks, caves, and sinkholes, can accelerate the transport of particulate pollutants from the surface to the groundwater zone (Xu et al. 2024). Recent studies have shown that MPs concentrations in cave water vary between 12 and 54 items/L, with cave sediments in Italy even showing abundances reaching 4,300 items/kg (Balestra et al. 2023a; Balestra and Bellopede 2023). Most MPs found in cave sediments and karst groundwater are in the form of fibers and fragments with sizes ranging from 3 to 20 μm (Balestra et al. 2023b; Balestra and Bellopede 2023; Shu et al. 2023). Meanwhile, in tropical karst areas, the rapid development of open-channel systems and the lack of protective layers in the unsaturated zone make karst aquifers highly susceptible to contamination from surface pollutants (Adji et al. 2017; Adji et al. 2019; Haryono et al. 2023).

Most available studies on microplastic contamination in karst environments have been conducted in temperate, Mediterranean, or subtropical settings, whereas tropical karst systems are still poorly represented in the global literature. This gap is important because tropical karst regions are characterized by high rainfall intensity, rapid recharge, thin or discontinuous soil cover, intense chemical weathering, and strong surface–subsurface connectivity, all of which may influence the fragmentation, mobilization, transport, and accumulation of MPs. In Java, the most densely populated island in Indonesia, karst regions such as Gunungsewu, Gombong, Sukolilo, and Kendeng are exposed to both natural hydrogeomorphic controls and increasing anthropogenic pressure, including settlement expansion, agriculture, tourism, and inadequate waste management. These conditions may create distinct pathways for MPs transfer into springs and underground rivers compared with karst systems in non-tropical regions. Research on MPs in tropical karst groundwater, particularly in Indonesia, remains very limited. Suprayogi et al. (2024) provided the first published evidence of MP contamination in underground rivers in the South Malang karst area, but multi-site assessments across different tropical karst systems are still lacking. In addition, Haryono et al. (2023) developed a specific approach for assessing land-use zoning and groundwater vulnerability in tropical cockpit karst; however, such vulnerability-based approaches have not yet been widely linked with emerging contaminants such as MPs. This indicates that environmental management in Indonesian tropical karst has largely focused on physical degradation, land-use pressure, and conventional agricultural or chemical pollution, while MP contamination remains an underrecognized threat to karst groundwater resources.

Tropical karst regions in Indonesia are characterized by intense chemical weathering and thin to discontinuous soil cover, with some areas having almost no protective overburden (Naufal et al. 2025). The Gunung Sewu karst region in southern Java is one of the largest and most highly developed tropical karst landscapes in Indonesia, and it serves as a major water source for surrounding communities. Previous hydrogeological studies have demonstrated spatial variability in karstification degree, aquifer storage capacity, and seasonal hydrogeochemical dynamics, indicating strong connectivity between surface processes and groundwater systems (Adji et al. 2016; Adji et al. 2019). Beyond Gunung Sewu, several other karst regions in Java, including Gombong, Jonggrangan, Sukolilo, Kendeng, and Rengel, also host springs that are widely used by local communities for drinking and domestic water supply. However, population growth and land-use conversion have increased settlement expansion, often without adequate drainage and waste management infrastructure. These conditions may accelerate the transfer of surface-derived pollutants into karst aquifers, particularly in areas where rapid infiltration and limited natural filtration occur (Naufal et al. 2025).

Despite increasing evidence of microplastic contamination in groundwater, the occurrence, spatial variability, and controlling mechanisms of microplastics in karst aquifers remain poorly understood, particularly in tropical karst regions. Recent studies have shown that karst systems can provide rapid pathways

for the transfer of microplastics from the surface into groundwater through surface water–groundwater hydraulic exchange, conduit flow, fractures, caves, underground rivers, and exposed recharge zones (Balestra et al. 2023b; Shu et al. 2023; Wei et al. 2024). However, most available evidence has been derived from temperate, subtropical, and Mediterranean karst regions, as well as karst plateaus in China and Europe, while tropical karst systems in Indonesia have rarely been investigated systematically. Tropical karst aquifers are characterized by high rainfall, rapid infiltration, thin soil cover, strong surface–subsurface connectivity, and increasing anthropogenic pressures from settlements, agriculture, tourism, and domestic activities. These conditions may generate distinct patterns of microplastic transport, accumulation, and exposure compared with non-tropical karst systems. Therefore, microplastic contamination in karst groundwater should not be treated merely as a pollution issue, but also as an important indicator for understanding karst hydrogeology, aquifer vulnerability, and groundwater resource protection (Xu et al. 2024).

To address these gaps, this study investigates the occurrence and water–sediment distribution of suspected MPs in tropical karst aquifers across Java Island, Indonesia, using paired water and sediment evidence from springs and underground rivers in seven karst regions with different geomorphological, hydrogeological, karst-development, and anthropogenic settings. The specific objectives are to determine the abundance, morphology, size, color, and polymer composition of suspected MPs in karst groundwater and associated spring sediments; compare spatial variations in suspected MP occurrence among karst systems with different degrees of aquifer development and human pressure; and evaluate the implications of suspected MP occurrence for groundwater quality management and spring protection in tropical karst landscapes. The main contribution of this study is its integration of MP characteristics with karst hydrogeological variability and catchment-scale anthropogenic drivers in an underrepresented tropical setting. By combining microplastic evidence with karst hydrogeological interpretation, this study provides a baseline for long-term monitoring, risk assessment, and protection of karst groundwater resources used for domestic water supply in Indonesia and other tropical regions (Shu et al. 2023; Suprayogi et al. 2024; Wei et al. 2024; Xu et al. 2024).

2. Materials and Methods

2.1. Study area

This study was conducted in seven tropical karst regions across Java Island, Indonesia: Gunungsewu, Gombong, Jonggrangan, Sukolilo, Kendeng/Rembang, Tuban, and Rengel Karst (Fig. 1). These karst regions have developed under a humid tropical monsoon climate, where relatively high rainfall promotes intensive carbonate dissolution, the formation of underground drainage systems, and the development of springs and underground rivers. In such settings, rainfall can rapidly infiltrate into the aquifer through closed depressions, ponors, swallow holes, fractures, caves, and conduit networks. This hydrogeological setting makes tropical karst aquifers highly dynamic, but at the same time highly vulnerable to the rapid transfer of surface-derived pollutants, including microplastic particles (Adji et al. 2019; Haryono et al. 2023).

Physiographically, the study sites represent two major karst belts in Java: the southern and northern karst zones. Gunungsewu, Gombong, and Jonggrangan are located in the southern part of Java and are associated with the Southern Mountains. Gunungsewu is one of the most developed tropical karst landscapes in Indonesia, characterized by cockpit and cone karst morphology, extensive underground river systems, dominant conduit flow, and rapid recharge. Gombong, also known as Karangbolong Karst, is developed mainly within the reef limestone of the Kalipucang Formation and contains numerous caves and springs, indicating a well-developed karst aquifer system. Jonggrangan Karst, in contrast, represents a relatively isolated structural karst developed in the Jonggrangan Formation, where carbonate rocks overlie older volcanic rocks and groundwater flow is more localized and strongly controlled by fractures.

The northern karst zone, represented by Sukolilo, Kendeng/Rembang, Tuban, and Rengel, shows different geological and hydrogeological characteristics. Sukolilo and Kendeng/Rembang form part of the folded karst landscapes of the Kendeng–Rembang zone, where springs play an important role in local water supply and groundwater flow is strongly influenced by geological structures. Tuban represents a northern coastal reef-platform karst system, with springs that commonly show diffuse-flow characteristics and Ca-HCO_3 hydrochemical facies. Rengel, which developed within the Paciran Formation, is a younger low-relief fluviokarst system, but it hosts the large Ngerong Spring, which reflects a mixed fracture–conduit flow system. The differences in geology, geomorphology, hydrogeological characteristics, and anthropogenic pressures among the study areas are summarized in Table 1.

Table 1. Comparative characteristics of the investigated karst regions

Karst Region	Springs / Underground Rivers	Geology	Geomorphological Type	Hydrogeological Characteristics	Anthropogenic Activities	References
Gunungsewu	Guntur, Petoyan, Baron, Sumurup, Beton, Kalisuci, Pindul, Kakap, Teleng/Sooka, Selare	Wonosari and Punung Formations (Miocene)	Cockpit / cone karst	Large underground river systems, conduit-dominated flow, rapid recharge	Tourism, agriculture, settlements	Haryono et al. (2023)
Gombong	Petrak Cave, Kalikarak, Jatijajar, Jumlang, Kalisirah	Kalipucang Formation, reef limestone	Southern hill karst	Numerous springs and caves, well-developed aquifer system	Agriculture and settlements	Priambada (2021); Rahmawati et al. (2020)
Jonggrangan	Sumitro, Mudal, Anjani	Jonggrangan Formation (Early Miocene), carbonate rocks overlying older volcanic rocks	Isolated structural karst	Local groundwater system, fracture-dominated flow	Agriculture, tourism, settlements	Pambudi et al. (2026); Pratama (2019); Pratama et al. (2021)
Sukolilo	Boyo and Ngesong	Tawun, Bulu, Wonocolo, and Ngrayong Formations	Folded Kendeng karst	28 springs functioning as community water-supply sources	Intensive agriculture, production forest, settlements	Tommy et al. (2025)
Kendeng/Rembang	Brubulan Tahunan and Sumber Semen	Neogene limestone of the northern Java belt	Folded Kendeng karst	Scattered springs, fracture-controlled flow	Mining, agriculture, settlements	Dewantara (2019)
Tuban	Belik Anget and Lamijah	Northern coastal limestone	Reef-platform karst	Springs with diffuse-flow characteristics, dominated by Ca-HCO ₃ hydrochemical facies	Industry, agriculture, settlements	Mifta (2014)
Rengel	Ngerong	Paciran Formation (Plio-Pleistocene)	Young low-relief fluviokarst	Large Ngerong Spring, mixed fissure-conduit flow	Local mining, agriculture, settlements	Adji et al. (2019); Mujib (2015)

The seven karst regions were selected to represent variations in karst development, groundwater flow regimes, spring and underground river systems, and human pressures. The sampling locations include areas influenced by settlements, agriculture, tourism, production forests, mining, and industrial activities. This range of settings allows the distribution of microplastics in tropical karst groundwater to be evaluated in relation to surface pollutant sources, karst hydrogeological characteristics, and the interaction between both factors.

2.2. Research design

This study employed a multi-site exploratory–comparative design to assess the occurrence, abundance, and characteristics of microplastics (MPs) in tropical karst groundwater across Java Island. This approach was adopted because baseline information on MPs in Indonesian tropical karst aquifers remains scarce, whereas karst hydrogeological conditions are highly heterogeneous and may strongly influence the transfer of particles from the surface into groundwater systems. The main units of analysis were karst groundwater outlets, including springs and underground rivers. Water samples were used to represent MPs transported by active groundwater flow during sampling, while sediment samples reflected particle accumulation through deposition and retention processes. The combined analysis of water and sediment therefore provides a more comprehensive understanding of MP transport and accumulation within karst aquifer systems.

The study covered seven karst regions, namely Gunungsewu, Gombong, Jonggrangan, Sukolilo, Kendeng/Rembang, Tuban, and Rengel. These regions were selected purposively to represent variations between the southern and northern karst zones of Java, as well as differences in aquifer development, groundwater flow type, spring and underground river systems, community water use, and anthropogenic pressures. The selected sites include areas influenced by settlements, agriculture, tourism, production forests, mining, and industrial activities, allowing MP contamination to be evaluated within a broad range of hydrogeological and land-use settings.

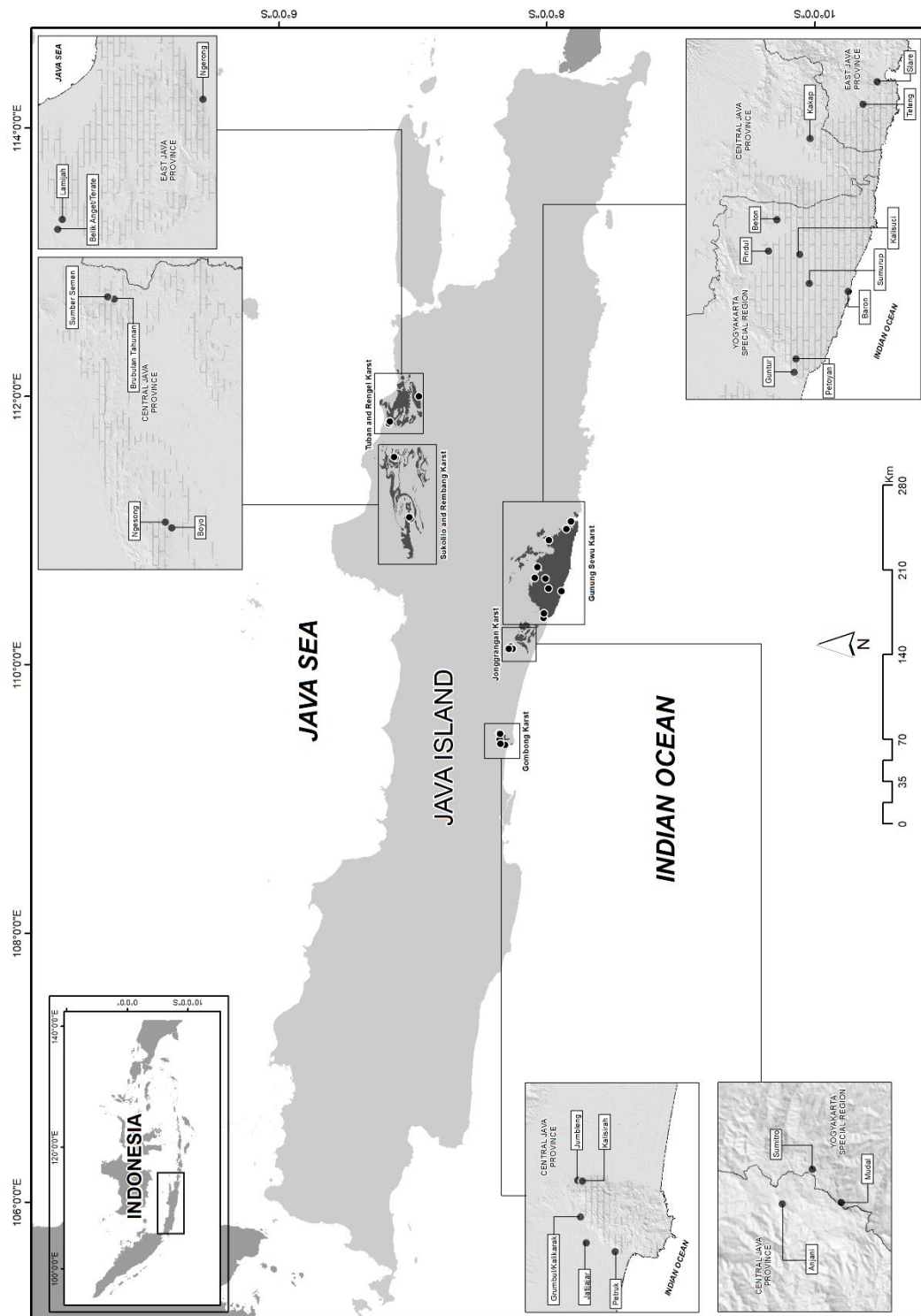


Fig. 1. Location of microplastic sampling in the karst region of Java Island

2.3. Sampling

Sampling was conducted at 25 sites representing springs and underground rivers across the seven karst regions. The sampling sites included Sumitro, Mudal, and Anjani Cave in Jonggrangan Karst; Petruk Cave, Kalikarak, Jatijajar Cave, Jumlung, and Kalisirah in Gombong Karst; Sendang Boyo and Sendang Ngesong Cave in Sukolilo Karst; Brubulan Tahunan and Sumber Semen in Kendeng/Rembang Karst; Belik Anget and Lamijah in Tuban Karst; Ngerong in Rengel Karst; and Guntur, Petoyan/Ngeleng, Baron, Sumurup, Beton, Kalisuci, Pindul Cave, Kakap, Teleng/Sooka, and Selare in Gunungsewu Karst. These sites were selected based on three main considerations: hydrogeological representation, community water use, and potential anthropogenic pressures within recharge areas or around groundwater outlets. Hydrogeological representation was considered by including springs and underground rivers with conduit, diffuse, fracture-dominated, and mixed-flow characteristics. Community water use was also considered because many of the selected springs and underground rivers are used for domestic supply, drinking water, irrigation, or other local activities.

Water samples were collected using sterile glass bottles with volumes ranging from 500 to 1150 mL, depending on discharge conditions, site accessibility, and field constraints. The actual volume of each sample was recorded to allow MP abundance to be normalized into particles/L or particles/100 mL. Before sampling, each bottle was rinsed three times with local water. Samples were collected from active flow sections or main groundwater outlets to minimize bias from stagnant water or localized accumulation. This sampling-volume approach follows procedures commonly applied in microplastic studies of karst systems and underground rivers (Balestra et al. 2024; Suprayogi et al. 2024). Sediment samples were collected from the same 25 locations as the groundwater samples to allow paired comparison between actively transported MPs in water. Sediment samples, representing accumulated MPs, were collected from surface sediments in depositional zones around springs or underground rivers. The uppermost sediment layer, approximately 0–5 cm, was targeted because it is directly exposed to flowing water and is likely to record recent MPs deposition. Approximately 250 g of sediment was collected at each site and stored in clean glass containers or wrapped in aluminum foil to minimize plastic contamination. This sediment sampling approach is consistent with previous microplastic studies in subterranean karst habitats and underground river systems (Balestra et al. 2024; Suprayogi et al. 2024).

2.4. Preparation and extraction of microplastic samples

Potential contamination was reduced throughout sampling, sample preparation, and laboratory analysis by reducing the use of plastic materials as much as possible. Sterile glass bottles were used as sample containers, and all tools that came into direct contact with the samples were cleaned before use. After collection, the samples were immediately sealed and transported to the laboratory under cool conditions. During laboratory preparation, Petri dishes and filters were kept covered whenever they were not being processed to reduce airborne contamination. The working area was cleaned before analysis, and microscopic observations were carried out on dried samples kept in covered glass containers. These precautions were applied to reduce, although not completely eliminate, the introduction of external fibers or foreign particles that could interfere with visual particle identification.

Field blanks, procedural blanks, and recovery tests were not available for all sampling batches. Therefore, the visually identified particle counts are treated as suspected MPs and should be interpreted as baseline estimates; only particles confirmed by FTIR are regarded as verified synthetic polymers. This limitation is particularly relevant for fiber-shaped particles, which may be susceptible to airborne contamination or visual misclassification.

Water samples were filtered through 0.45 μm membrane filters to retain microplastic particles. The residues on the filters were then treated with 30% H_2O_2 to remove organic matter, and the oxidation process was conducted for 24 h at approximately 75°C. After oxidation, particle separation was assisted using a 10% NaCl solution based on density differences among plastic particles, organic residues, and mineral grains. For sediment samples, the sediments were first dried under covered conditions and then weighed so that the results could be expressed as particles/g dry weight. Sediment subsamples were mixed with 10% NaCl solution, stirred, and left to settle until density separation occurred. The supernatant containing lighter particles was subsequently filtered through 0.45 μm membrane filters. The retained residues were transferred to glass Petri dishes and dried at room temperature under covered conditions before microscopic observation.

2.5. Identification and characterization of microplastics

Particles retained on the filters were examined using an Olympus BX53 trinocular research microscope. Initial identification was carried out based on visual characteristics, including particle number, form/shape, color, and size. The identified MPs were classified into five morphological categories: fibers, fragments, films, foams, and pellets/beads. Particle size was measured using digital image analysis software, with the maximum

length, diameter, or surface area recorded according to particle morphology. A subset of visually identified particles was further analyzed using Fourier Transform Infrared Spectroscopy (FTIR) to confirm polymer composition. FTIR analysis was performed using a Shimadzu IRTracer-100 AH equipped with the LabSolutions IR spectral library. Spectra with a match rate of >70% were accepted as valid polymer identification, following the approach applied in previous studies of microplastics in karst groundwater systems (Wei et al. 2024).

2.6. Data analysis

The abundance of microplastics (MPs) in groundwater samples was calculated by dividing the total number of identified particles by the volume of each sample and normalizing the values to particles/100 mL. For sediment samples, MP abundance was expressed as particles/5 g of dry sediment. The analyzed variables included total abundance, morphological form, color, size, dominant form, and polymer composition. MPs were classified into fibers, fragments, films, foams, and pellets, and descriptive statistics, including minimum, maximum, mean, median, range, and percentage composition, were used to summarize their distribution. The data were grouped and compared based on karst region, groundwater outlet type, dominant land use, and karst development stage. Groundwater outlet types were classified into springs and underground rivers, while land-use categories included residential areas, agriculture, mixed gardens, production forests, and mining areas. Karst development stages were classified into undeveloped, moderately developed, developed, and allogenic recharge points. For sediment samples, additional comparisons were made to evaluate MP accumulation and retention patterns based on total abundance, dominant form, percentage composition, flow type, land cover, and karst development stage.

Throughout the results, counts derived from microscopy are reported as suspected MPs, whereas polymer-specific statements refer only to the FTIR-confirmed subset.

Polymer composition was assessed using FTIR analysis on selected visually identified particles, with spectra match rates greater than 70% accepted for polymer identification. The identified particles were grouped into synthetic polymers, including PE, PP, polyamide/nylon, PET, and EVA, and anthropogenic cellulosic fibers (ACFs), such as Tencel, cupra, ramie, and paper-derived cellulose. The results were presented using tables, stacked bar charts, percentage composition charts, boxplots, and representative microphotographs. Interpretation of potential MP sources was conducted cautiously by integrating abundance, morphology, color, polymer type, land use, flow type, and karst hydrogeological context, without implying direct causal relationships.

3. Results

3.1. General findings

According to Fig. 2, suspected MPs were visually identified in all 25 groundwater-outlet water samples, with abundances ranging from 26 to 78 particles/100 mL. The highest abundance was recorded at PW1 in the Sukolilo Karst Area, with 78 particles/100 mL, followed by KB2 in the Gombong Karst Area, with 68 particles/100 mL. In contrast, the lowest abundance was observed at KP2 in the Jonggrangan Karst Area, with 26 particles/100 mL. In addition, Fibers were the dominant form at most sampling sites, followed by fragments, while films, foams, and pellets were detected only in relatively small numbers. RM1 was the main exception, where fragment abundance exceeded that of fibers. These spatial differences may reflect variations in local sources, surrounding land use, and the transport and redistribution of particles through different karst flow pathways.

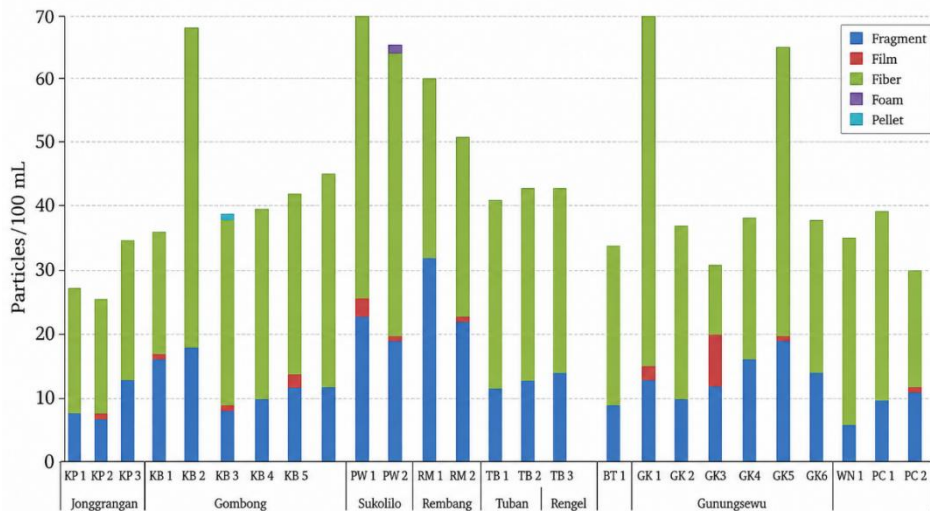


Fig. 2. MP abundance and composition at each sampling site

3.2. Abundance variations

Sukolilo karst also showed the highest mean regional abundance, reaching 48 particles/100 mL, followed by Gombong and Gunungsewu, with mean values of 29 and 26 particles/100 mL, respectively. In contrast, Jonggrangan recorded the lowest mean abundance, at 19 particles/100 mL (Fig. 3). The distribution of particle forms also varied among regions. Fragments were most abundant in Rembang, whereas films occurred only in low numbers across the study areas. Foam was detected only in Sukolilo, while pellets were observed only in Gombong. These regional differences are descriptive and may reflect the combined influence of hydrogeological conditions, land-use characteristics, and local anthropogenic pressures.

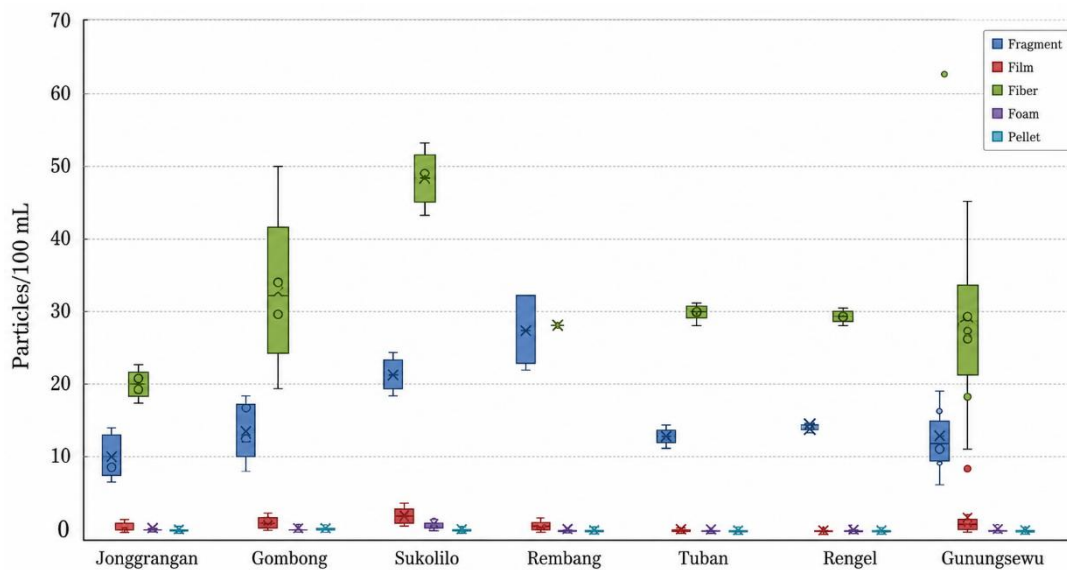


Fig. 3. Distribution of MP forms in karst areas, showing variation among fragments, films, fibers, foams, and pellets

3.3. Microplastic variations based on flow type, land use, and karst development

3.3.1. MPs and flow type

Both springs and underground rivers contained suspected MPs, with fibers as the dominant form in both types of outlets (Fig. 4). Overall abundance was higher in springs, while foam and pellets were found only in underground rivers. This pattern may suggest that springs collect particle inputs from wider recharge areas. However, this interpretation should be treated with caution because discharge and seasonal hydrological changes were not measured directly.

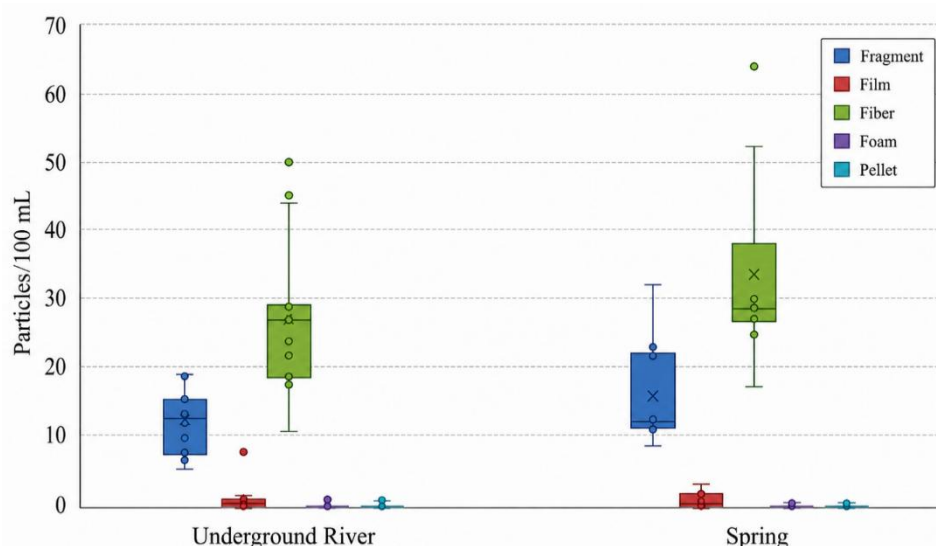


Fig. 4. Distribution of MP forms in underground river and spring water

3.3.2. MPs and anthropogenic activities

Suspected MPs occurred across all land-use categories, with fibers as the dominant form in every category (Fig. 5). As shown in the figure, fiber abundance varied more widely than the other particle forms, particularly in residential areas, while fragments were also present across several land-use settings. Films, foams, and pellets occurred only in small numbers. This pattern suggests that the observed particles may originate from multiple sources, including domestic and textile-related activities, atmospheric deposition, and the movement of particles through connected karst pathways.

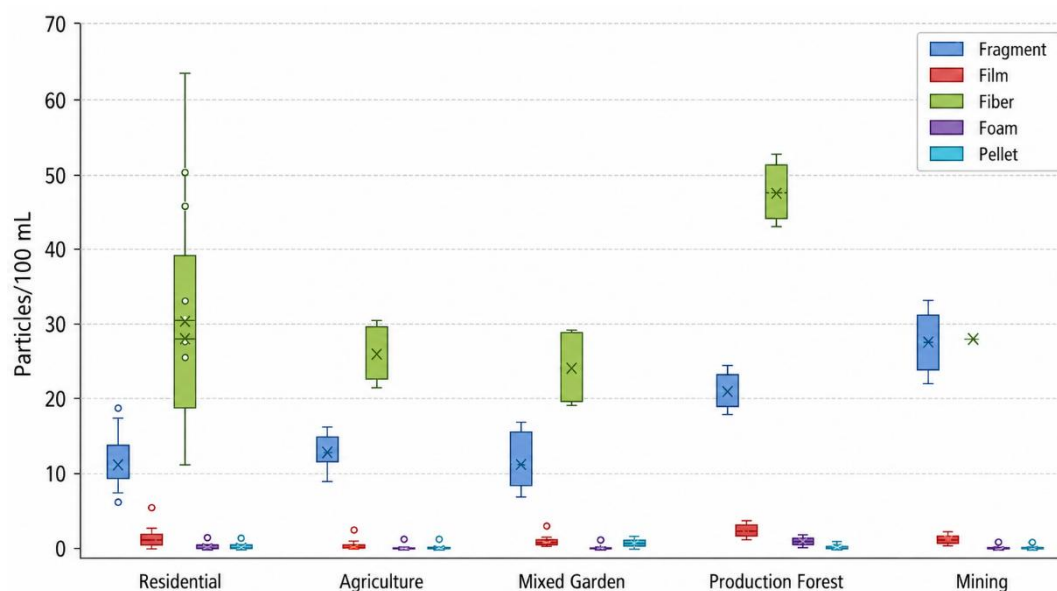


Fig. 5. Distribution of MP forms based on dominant land use

Residential sites showed the widest variation in fiber abundance, while fragments were more common in mining areas and production forests. Films, foam, and pellets made only a small contribution to the total abundance. The field observations in Fig. 6 show several possible sources, such as household waste, open dumping and burning, agricultural plastics, and other discarded plastic materials. These activities may help explain the observed patterns, although the exact sources could not be confirmed from this study.

3.3.3. MPs and karst development

All karst-development categories contained suspected MPs, with fibers and fragments as the dominant forms (Fig. 7 and Table 2). Fiber abundance was highest in the undeveloped category, ranging from 29 to 63 particles/100 mL, and lowest in the moderately developed category, at 18–29 particles/100 mL. This pattern shows that suspected MP occurrence was not limited to highly developed conduit systems, but was also found across less developed karst settings.

Table 2. Karst development categories

Karst Development Category	Flow Character	Sampling Location	References
Undeveloped	Diffuse flow	PW 1, PW 2, TB 1, TB 2, GK 1	Adji et al. (2019, 2023); Dewantara (2019)
Moderately developed	Diffuse–fissure flow	KP 1, KP 2, KB 1, KB 4, RM 1, RM 2, TB 3, BT 1, WN 1, PC 1, PC 2	Dewantara (2019); Fatchurohman et al. (2018); Fatoni et al. (2024); Mujib et al. (2024); Naufal et al. (2025); Pratama et al. (2021); Rahmawati et al. (2020)
Developed	Fissure–conduit flow	KP 3, KB 2, KB 3, KB 5, GK 2, GK 4, GK 6	Adji et al. (2019, 2023); Fatoni et al. (2024); Naufal et al. (2025); Nurkholis et al. (2019); Rahmawati et al. (2020)
Allogenic point	Allogenic recharge	GK 3, GK 5	Adji et al. (2019, 2023)

Allogenic points showed the highest film abundance, ranging from 1 to 8 particles/100 mL, while fragments were distributed more evenly, at 6–23 particles/100 mL. This pattern may be related to surface runoff carrying plastic packaging and agricultural films from non-carbonate catchments into the karst system. However, the available data do not allow these materials to be linked to a specific source with certainty.



Fig. 6. Anthropogenic sources: a) Indiscriminate waste disposal (Rembang); b) Agricultural plastic waste (Tuban); c) Indiscriminate waste disposal (Tuban); d) Burning of plastic waste (Sukolilo); e) Open landfill (Gunungsewu); f) Plastic filter covering fruit (Sukolilo); g) Fish ponds made of plastic (Sukolilo); h) Washing clothes in water bodies (Gombong)

3.4. Morphology, color, size, and polymer characteristics of MPs

3.4.1. Shape and color

Fibers accounted for 50–82% of the suspected MPs across the sampling sites and were followed by fragments (Fig. 8). Films were most noticeable at GK3, while foam and pellets each contributed less than 3% and were found at only one site. The particles also showed a range of colors, although transparent fibers were the most common form (Fig. 9). Transparent fibers remained dominant across most outlet types, land-use categories, and levels of karst development. RM1 and GK3 showed a different pattern, with black fragments as the dominant form. This suggests that local sources may still influence particle characteristics and that these particles were not fully mixed during subsurface transport. The main characteristics of each sampling site are summarized in Table 3.

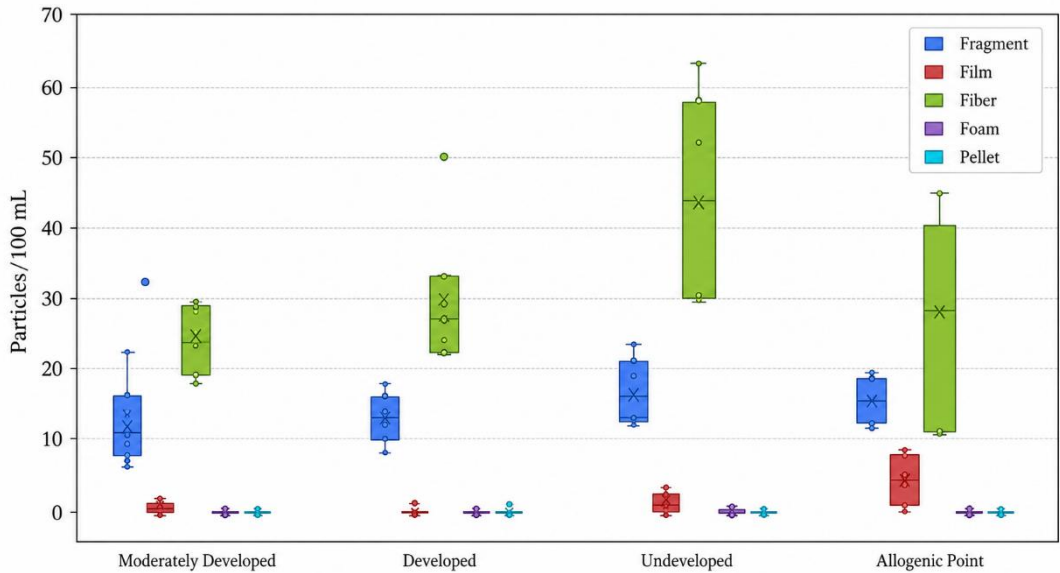


Fig. 7. Distribution of MPs based on karst development

The 25 sampling sites included springs and underground rivers from different land-use and karst settings. Even with these differences, fibers and transparent particles were the most common at most sites. However, some local variations suggest that nearby pollution sources and different groundwater flow paths may have influenced the particle patterns.

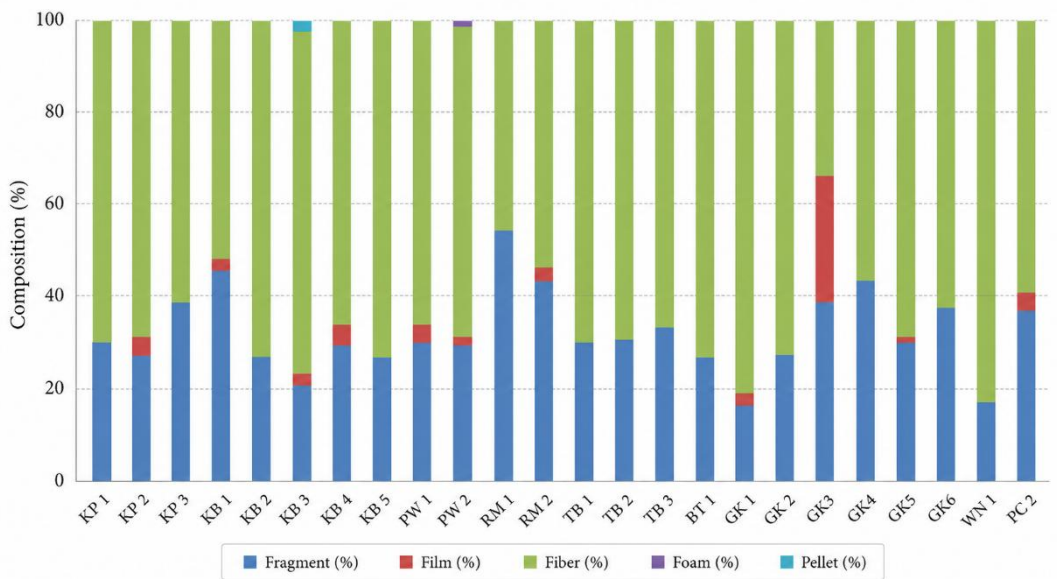


Fig. 8. Percentage composition of MP forms

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Fig. 9. Color and shape of MPs

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Table 3. Characteristics of sampling sites across the studied karst areas, including karst system type, dominant land use, karst development stage, dominant microplastic form, and dominant color

Code	Site name	Karst area	Karst flow type	Dominant landuse	Karst development	Dominant form	Dominant color
KP 1	Sumitro	Jonggrangan	Underground River	Residential	Moderately Developed	Fiber	Transparent
KP 2	Mudal	Jonggrangan	Underground River	Residential	Moderately Developed	Fiber	Transparent
KP 3	Anjani	Jonggrangan	Underground River	Agriculture	Developed	Fiber	Transparent
KB 1	Petruk Cave	Gombong	Underground River	Mixed Garden	Moderately Developed	Fiber	Transparent
KB 2	Kalikarak	Gombong	Underground River	Residential	Developed	Fiber	Transparent
KB 3	Jatijajar Cave	Gombong	Underground River	Mixed Garden	Developed	Fiber	Transparent
KB 4	Jumbleng	Gombong	Spring	Residential	Moderately Developed	Fiber	Transparent
KB 5	Kalisirah	Gombong	Spring	Residential	Developed	Fiber	Transparent
PW 1	Sendang Boyo	Sukolilo	Spring	Production Forest	Undeveloped	Fiber	Transparent
PW 2	Sendang Ngesong	Sukolilo	Underground River	Production Forest	Undeveloped	Fiber	Transparent
RM 1	Brubulan Tahunan	Rembang	Spring	Mining	Moderately Developed	Fragment	Black
RM 2	Sumber Semen	Rembang	Spring	Mining	Moderately Developed	Fiber	Transparent
TB 1	Belik Anget	Tuban	Spring	Agriculture	Undeveloped	Fiber	Transparent
TB 2	Lamijah	Tuban	Spring	Agriculture	Undeveloped	Fiber	Transparent
TB 3	Ngerong	Rengel	Underground River	Agriculture	Moderately Developed	Fiber	Transparent
BT 1	Guntur	Gunungsewu	Spring	Agriculture	Moderately Developed	Fiber	Transparent
GK 1	Ngeleng	Gunungsewu	Spring	Residential	Undeveloped	Fiber	Transparent
GK 2	Baron	Gunungsewu	Underground River	Residential	Developed	Fiber	Transparent
GK 3	Sumurup	Gunungsewu	Underground River	Residential	Allogenic Point	Fragment	Black
GK 4	Beton	Gunungsewu	Underground River	Agriculture	Developed	Fiber	Transparent
GK 5	Kalisuci	Gunungsewu	Underground River	Residential	Allogenic Point	Fiber	Transparent
GK 6	Pindul Cave	Gunungsewu	Underground River	Residential	Developed	Fiber	Transparent
WN 1	Kakap	Gunungsewu	Underground River	Residential	Moderately Developed	Fiber	Transparent
PC 1	Teleng Sooka	Gunungsewu	Underground River	Residential	Moderately Developed	Fiber	Transparent
PC 2	Selare	Gunungsewu	Spring	Residential	Moderately Developed	Fiber	Transparent

3.5. MPs in sediment: evidence of accumulation and retention in karst systems

Table 4 shows that fibers were the dominant form in most water and sediment samples. However, fragments or films were more common at several sediment sites. This difference may be related to how each particle type moves in the karst system. Lightweight fibers can be carried more easily by flowing water, while fragments and films are more likely to settle and build up in low-flow or depositional areas (Cheng et al. 2024; Riddell et al. 2023; Shu et al. 2023).

Suspected MPs were found in all sediment samples, with abundances ranging from 41 to 211 particles/5 g (Fig. 10). The highest value was recorded at GK5 in Gunungsewu, reaching 211 particles/5 g, while the lowest was found at KB4 in Gombong, with 41 particles/5 g. Fibers made up more than 70% of the particles at five sites, fragments were dominant at four sites, and films were the main form at KB1. These differences show that the type of particles stored in sediment varied among locations.

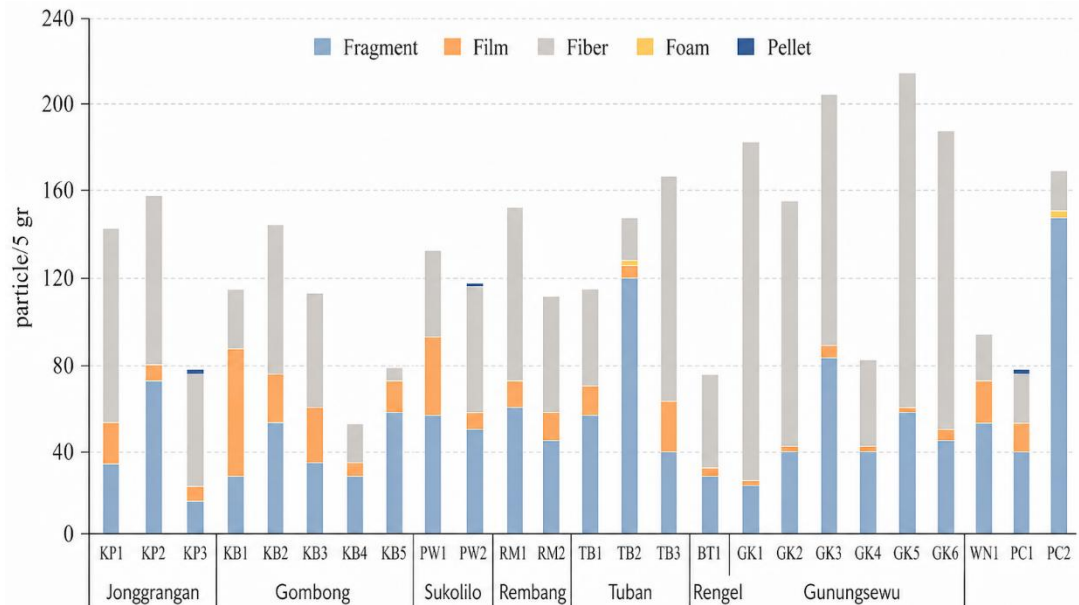
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Table 4. Comparison of the abundance and shape of MPs in groundwater and sediment

Site Code	Water Type	MPs Abundance in Groundwater (particles/100 mL)	MPs Abundance in Sediment (particles/5 g)	Dominant MPs Form in Groundwater	Dominant MPs Form in Sediment
KP 1	Underground River	27	30	Fiber	Fiber
KP 2	Underground River	26	148	Fiber	Fiber
KP 3	Underground River	35	65	Fiber	Fiber
KB 1	Underground River	36	103	Fiber	Film
KB 2	Underground River	68	133	Fiber	Fiber
KB 3	Underground River	39	101	Fiber	Fiber
KB 4	Spring	42	41	Fiber	Fragment
KB 5	Spring	45	67	Fiber	Fragment
PW 1	Spring	78	121	Fiber	Fiber
PW 2	Underground River	65	105	Fiber	Fiber
RM 1	Spring	60	143	Fragment	Fiber
RM 2	Spring	51	99	Fiber	Fiber
TB 1	Spring	41	102	Fiber	Fragment
TB 2	Spring	43	138	Fiber	Fragment
TB 3	Underground River	43	156	Fiber	Fiber
BT 1	Spring	34	63	Fiber	Fiber
GK 1	Spring	65	174	Fiber	Fiber
GK 2	Underground River	37	144	Fiber	Fiber
GK 3	Underground River	31	199	Fragment	Fiber
GK 4	Underground River	38	69	Fiber	Fiber
GK 5	Underground River	65	211	Fiber	Fiber
GK 6	Underground River	38	180	Fiber	Fiber
WN 1	Underground River	35	81	Fiber	Fragment
PC 1	Underground River	39	65	Fiber	Fragment
PC 2	Spring	30	160	Fiber	Fragment

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Fig. 10. Abundance of MPs in sediment samples

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Compared with water samples, sediment samples contained higher proportions of fragments and films (Fig. 11). This pattern suggests that depositional areas may temporarily hold these particles as they settle from the water. However, during periods of stronger flow, some of the stored particles may be released again. Therefore,

sediments can act both as a record of particle accumulation and as a possible secondary source of contamination.

Fibers were the dominant form in sediment samples across all land-cover categories (Fig. 12). Residential areas showed the highest median fiber abundance and the widest range of values. Agricultural sites, however, showed the widest range and the highest maximum abundance of fragments, which may be linked to the breakdown of agricultural plastics. Pellets were found only in small numbers, while foam was not detected in any land-cover category.

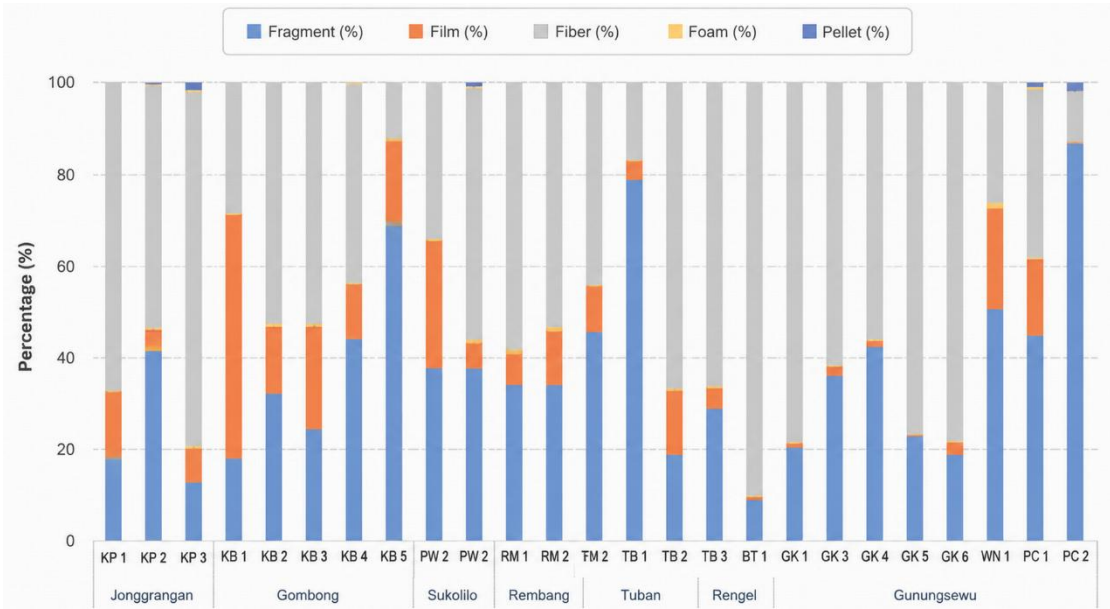


Fig. 11. Percentage of MP forms in sediment

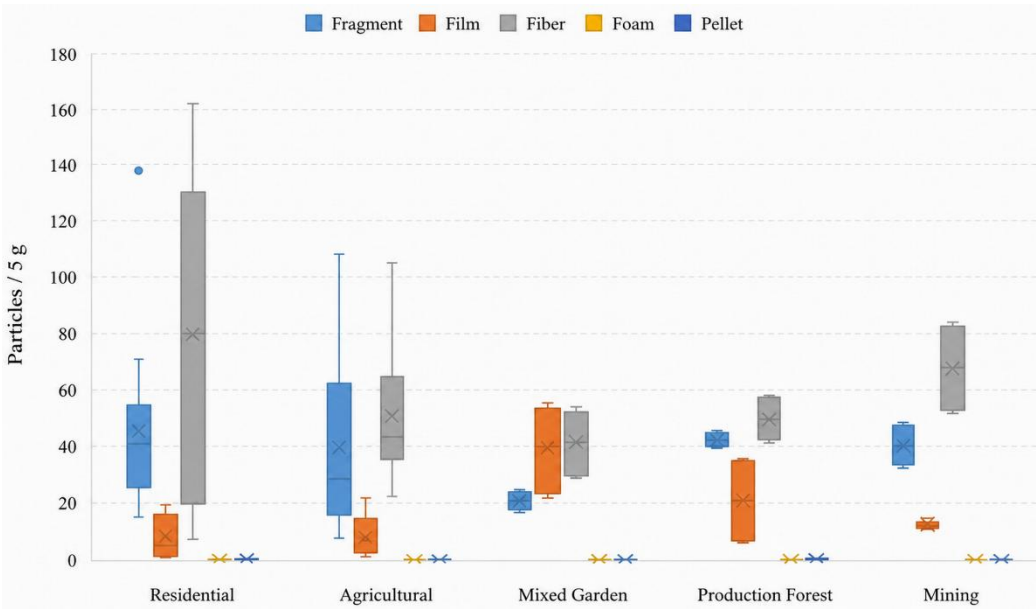


Fig. 12. Distribution of MPs in sediments based on dominant land use

Underground-river sediments had a median fiber abundance of 72 particles/5 g, compared with 29 particles/5 g for fragments and about 7 particles/5 g for films (Fig. 13). In spring sediments, fiber abundance was lower, while the median fragment abundance reached 45 particles/5 g, about 55% higher than in underground-river sediments. Foam and pellets were almost absent in both outlet types. This difference suggests that particle composition in sediment may vary between springs and underground rivers.

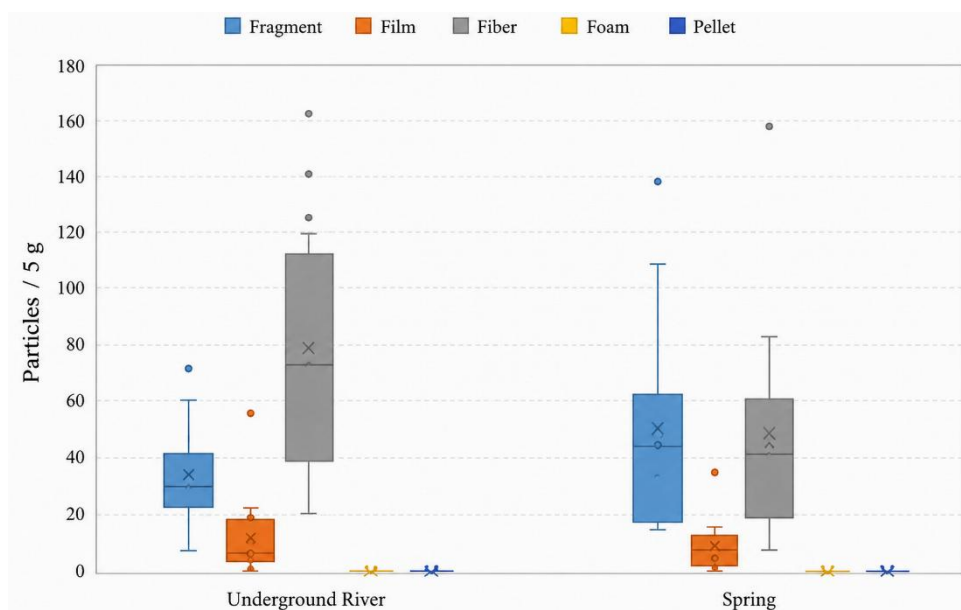


Fig. 13. Distribution of MPs in sediments based on flow type

Allogenic recharge points showed the highest median abundances of both fibers and fragments, reaching 143 and 59 particles/5 g, respectively (Fig. 14). This pattern may indicate that concentrated surface inflow from non-carbonate catchments carries more particles into the karst system. These particles may then settle and accumulate in nearby depositional areas.

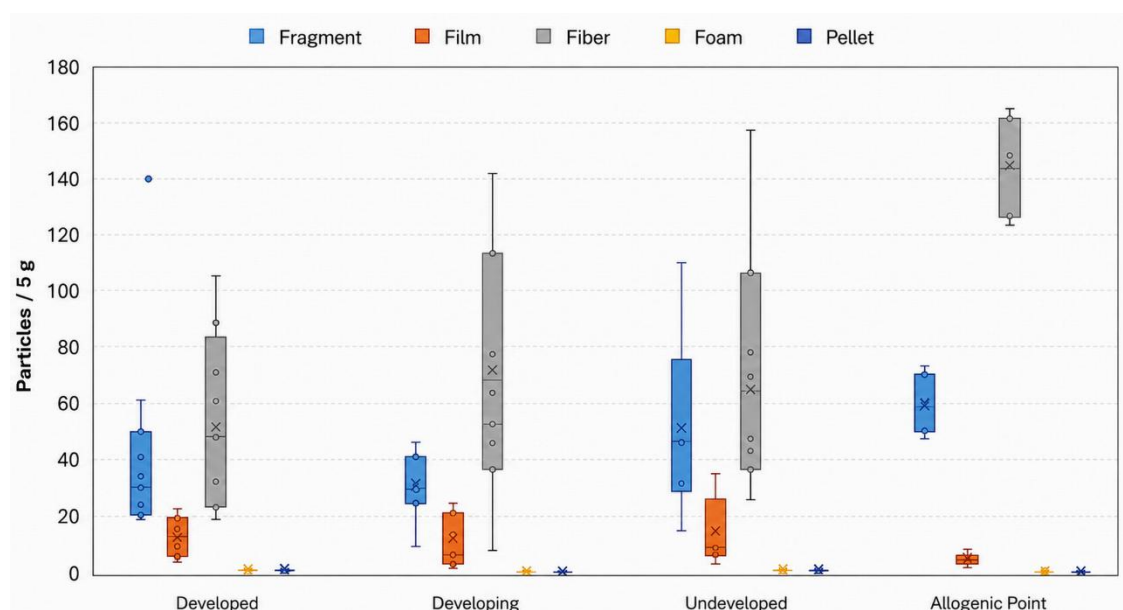


Fig. 14. Distribution of MPs in sediments based on karst development

FTIR analysis was carried out on 17 particles from 10 sediment samples that contained particles larger than 500 μm (Table 5). Of these particles, 70.6% were identified as synthetic polymers, mainly polyethylene (PE; 29.4%), polypropylene (PP; 17.6%), and polyamide/nylon (11.8%), with smaller amounts of PET and EVA. The remaining 29.4% were identified as anthropogenic cellulosic fibers. These results show that visual identification alone may overestimate the actual abundance of synthetic microplastics, particularly when fiber-like particles are present.

Table 5. Identification of polymer types based on FTIR analysis

Sampel code	Range Skor (Top 3)	Library	Name (Top 3)	Interpretation
TB 1	732–739	T-Polymer2	EVOH, Nylon11, Ramie	Polyamide (Nylon-like)
	720–725	ATR/T-Polymer2	Polyacetylene, Polyacetylene, Tencel	ACF
TB 2	721–726	T/ATR-Polymer2	Polyacetylene, Soy Bean Powder, D_Protein2	Polyamide (Nylon-like)
RM 1	732–738	T/ATR-Polymer2	PE, Chlorinated PE, Ethylene/Ethyl Acrylate	Weathered PE
PC 1	754–773	ATR/T-Polymer2	Paper, Ramie, Tencel	ACF
PC 2	786–799	ATR-Polymer2	Paper, Cupra, Tencel	ACF
WN 1	753–762	ATR/T-Polymer2	Tencel, Cupra, Polyacetylene	ACF
GK 2	753–815	ATR/T-Polymer2	Polyethylene, HDPE, Polyethylene	Weathered PE
	704–710	ATR/T-Polymer2	EVA, EVA, EVA (33% VA)	EVA-based polymer
GK 3	753–759	ATR/T-Polymer2	Chlorinated PE, Ethylene/Propylene Copolymer, PE	Weathered PE
	756–768	ATR/T-Polymer2	PP, Isotactic PP, Paper	Polypropylene (PP)
	868–877	ATR/T-Polymer2	Polyester Film, Polyester Film, PET	PET
GK 4	795–816	ATR/T-Polymer2	PP, Isotactic PP, PP	Polypropylene (PP)
	769–782	ATR/T-Polymer2	PE, HDPE, Chlorinated PE	Weathered PE
GK 5	744–755	ATR/T-Polymer2	PP, Isotactic PP, PP	Polypropylene (PP)
	703–740	ATR/T-Polymer2	Polyacetylene, Polyacetylene, Bemberg (Cupra)	ACF
	844–882	ATR/T-Polymer2	PE, HDPE, PE	Polyethylene (PE)

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441 **4. Discussion**

442 The occurrence of suspected microplastics (MPs) in all groundwater samples shows that particle
443 contamination is widespread in tropical karst aquifers across Java. Abundances ranged from 26 to 78
444 particles/100 mL in springs and underground rivers. Although groundwater is often assumed to be protected by
445 soil, vegetation, and the unsaturated zone, this protection is limited in karst areas. Surface water and associated
446 particles can rapidly enter the aquifer through fractures, ponors, swallow holes, caves, sinking streams, and
447 conduit networks. Similar findings have been reported from karst areas in Italy, China, South Malang, Russia,
448 and Kentucky (Balestra et al. 2023a; Shu et al. 2023; Suprayogi et al. 2024; Filimonova et al. 2025; Norman
449 2024). The present study extends this evidence by documenting suspected MPs across seven karst regions with
450 different hydrogeological and human settings.

451 The spatial differences among Sukolilo, Gombong, Gunungsewu, Jonggrangan, Kendeng/Rembang, Tuban,
452 and Rengel cannot be explained by a single factor. MP distribution is more likely shaped by the interaction
453 between pollution sources at the surface and transport processes within the karst aquifer. Land use influences
454 the types and amounts of particles entering the system, while karst pathways control whether they are
455 transported rapidly, temporarily stored, or deposited in sediments. This interaction is especially important in
456 Java, where karst areas are affected by settlements, agriculture, tourism, mining, production forests, and other
457 local activities. Comparisons with other studies should nevertheless be made carefully because sampling
458 procedures, filter sizes, laboratory treatment, and identification methods differ considerably (Jeon and Kim
459 2024; Xu et al. 2024).

460 Suspected MPs occurred under all dominant land-use categories, with fibers as the most common form. In
461 residential areas, fibers may originate from laundry, domestic wastewater, synthetic textiles, household waste,
462 and local drainage. Similar sources have been reported in the Huixian karst wetland, where domestic waste and
463 agricultural runoff contributed to MP contamination, and fibers were linked to the washing of synthetic textiles
464 (Wei et al. 2024). Atmospheric deposition may also contribute because fibers can be carried through the air and
465 deposited by rainfall or directly onto soil, water bodies, sinkholes, and cave entrances (Wagner and Lambert
466 2018). Residential areas with limited drainage and waste management may therefore provide both continuous
467 and rainfall-related particle inputs.

468 Agricultural areas may contribute particles through fertilizer and pesticide packaging, plastic sacks, ropes,
469 nets, mulch, and other weathered materials. The occurrence of films is relevant because this form is commonly
470 linked to plastic bags, thin packaging, and agricultural plastics that can be easily carried by runoff. Studies in
471 Southwest China have shown that land use affects the abundance, shape, and polymer composition of MPs in
472 karst soils, where PE, PP, PVC, and PET are commonly found (Zhang et al. 2024). Agricultural films and
473 woven bags have also been linked to PE and PP particles that can move with water into karst groundwater (Wei
474 et al. 2024).

475 Fragments were relatively more common at some mining and production-forest sites. These particles may
476 come from hard plastics, packaging, tarpaulins, containers, and materials used during transport or field

activities. Larger plastics can break down through sunlight, heat, abrasion, rainfall, and mechanical disturbance. Once they reach dolines, sinkholes, ponds, or river inlets, the resulting fragments may be carried rapidly into connected underground drainage systems.

Both springs and underground rivers contained suspected MPs. Underground rivers represent active transport routes, particularly where surface water enters through caves, sinkholes, or sinking streams. Springs may collect particles from broader recharge areas and from several flow components within an aquifer. Therefore, particles found at a spring do not necessarily come from pollution near the outlet. They may reflect combined inputs from conduit, fissure, and diffuse flow across the wider catchment (Adji et al. 2019; Mujib et al. 2024).

The influence of karst development was not linear. Well-developed conduit systems can support rapid particle transport, while diffuse or less-developed systems may retain particles longer in the epikarst, fractures, cavities, or sediment pockets. However, relatively high abundances also occurred in some less-developed settings. This indicates that weak karst development does not automatically mean low vulnerability. Surface-source intensity, recharge type, catchment structure, and hydrological connectivity may be equally important.

Previous hydrogeological studies in Java support this interpretation. Petoyan Spring is dominated by diffuse flow under normal conditions, but conduit flow becomes more important during floods (Adji et al. 2016). Hydrochemistry in Gunungsewu is mainly controlled by water–rock interaction in the dry season, but rainfall dilution and conduit recharge become stronger in the wet season (Adji et al. 2017). These seasonal changes are relevant because particles are more likely to be mobilized during rainfall and flooding than during baseflow.

Karst systems in Gombong, Jonggrangan, Pindul, and Rengel also show different flow and storage conditions. Kalisirah and Kalikarak respond rapidly to rainfall because of well-developed conduits, while Jumbeng has lower karst development and different storage behavior (Rahmawati et al. 2020). In Pindul, conduit, fissure, and diffuse components occur together, but stored water is released more rapidly than in the Kedungbuntung system (Nurkholis et al. 2019). Springs in Jonggrangan also differ in aquifer development and hydrodynamic behavior (Pratama et al. 2021; Fatoni et al. 2024). Ngerong has considerable storage and a memory effect of 26.41 days, but it can still respond to rainfall within about eight hours (Mujib et al. 2024). These examples suggest that particles may move through rapid conduit transport as well as slower release from diffuse and fissure storage.

Allogenic recharge is particularly important in explaining particle transport. Surface runoff from non-carbonate catchments can carry soil, organic matter, domestic waste, and plastic debris into karst systems through inflowing rivers, ponds, and swallow holes. The higher occurrence of films at allogenic points is consistent with this process because thin plastic packaging and agricultural films can be easily transported by runoff. The COCKPIT-PLUS framework identifies ponds or swallow holes, inflowing rivers, lineament density, and distance to springs as important controls on groundwater vulnerability (Haryono et al. 2023). The present results suggest that this framework can also be applied to emerging particulate contaminants.

The distinction between allogenic and autogenic recharge is also important for management. Allogenic recharge can introduce pollutants rapidly with little filtration, while autogenic recharge may allow greater temporary retention in soil, epikarst, and fractures. Beton, which receives stronger allogenic recharge and more intensive land use, has been reported to be more sensitive to pollution than Guntur, which is more strongly influenced by autogenic recharge (Naufal et al. 2025). Although that study focused on nitrate, phosphate, and *E. coli*, the same source–pathway–target concept is relevant to MPs.

One of the main findings of this study is the difference between water and sediment. Fibers dominated most water samples, probably because their low density and flexible shape allow them to remain suspended and move through flowing water. Similar patterns have been reported from karst water in Italy and China (Balestra et al. 2023; Wei et al. 2024). In the Yulong River karst system, fibers dominated surface water and groundwater, while fragments were more common in sediments (Shu et al. 2023).

Sediments in the present study contained greater proportions of fragments and films at several sites. This suggests that depositional areas can temporarily store particles that are less mobile in flowing water. Their accumulation may be influenced by shape, density, surface roughness, interaction with mineral grains, and low-flow conditions. Sediment therefore records not only particle deposition, but also hydraulic sorting and possible later remobilization.

This difference has direct implications for monitoring. Water samples mainly represent conditions at the time of sampling and may change with rainfall, discharge, and turbulence. Sediments can provide a longer-term record of particle accumulation. Studies in Italian show caves have found that cave deposits retain fibers, polyester, and polyolefins associated with clothing, dust, lint, and tourism activities (Balestra and Bellopede 2023). MPs have also been reported in both water and sediment in the Classical Karst, showing the importance of examining underground water together with its deposits (Balestra et al. 2024). Including sediment therefore provides information that cannot be obtained from a single water sample.

Sediments may also become secondary sources. During low flow, particles can settle in depositional zones, but during floods they may be resuspended by stronger turbulence and shear stress. This process is likely

important in tropical karst areas, where rainfall can rapidly change hydraulic conditions. In the Huixian karst wetland, small particles were more easily mobilized during the rainy season and transported toward groundwater by runoff and infiltration (Wei et al. 2024). Although the present study used snapshot sampling, the high sediment abundances suggest that repeated deposition and remobilization may occur.

Particle shape, color, and polymer composition provide additional information about possible sources. Transparent fibers dominated most sites and may represent widespread textile, domestic, and atmospheric inputs. In contrast, black fragments dominated at RM1 and GK3, suggesting stronger local influences. These fragments may come from degraded hard plastics, waste burning, mining materials, or upstream allogenic inputs. However, color should be interpreted carefully because it can change through sunlight, weathering, biofouling, and abrasion (Wagner and Lambert 2018).

FTIR analysis confirmed that 70.6% of the examined particles were synthetic polymers, mainly PE, PP, polyamide/nylon, PET, and EVA, while 29.4% were anthropogenic cellulosic fibers. PE and PP are commonly associated with packaging, bags, containers, and agricultural materials, whereas PET and polyamide may originate from textiles, ropes, bottles, and synthetic fibers. The cellulosic particles show that visual identification alone can overestimate synthetic MP abundance. This problem is widely recognized because groundwater studies still use different sampling and identification procedures (Jeon and Kim 2024). Although only a subset of particles was analyzed by FTIR, its use allowed the visual results to be interpreted more cautiously.

The main contribution of this study is its integration of particle characteristics with tropical karst hydrogeology. Previous studies in Italy have documented MPs in cave water and sediments, especially in relation to fibers and tourism (Balestra et al. 2023a; Balestra and Bellopede 2023). Studies in China have examined surface water–groundwater exchange, seasonal changes, agricultural runoff, and MPs in rivers, wetlands, lakes, and soils (Shu et al. 2023; Wei et al. 2024; Zhang et al. 2024). In Indonesia, MPs have been reported in underground rivers in South Malang, while research in Kentucky has shown their occurrence even in relatively undisturbed karst environments (Suprayogi et al. 2024; Norman 2024). The present study adds a broader comparison across seven tropical karst regions and links particle patterns with land use, outlet type, karst development, allogenic recharge, and sediment accumulation.

Overall, suspected MP distribution reflects the combined effects of human pressure, tropical rainfall, limited protective cover, open recharge features, allogenic inflow, and strong surface–groundwater connectivity. Fibers appear to represent widespread domestic, textile, and atmospheric inputs, while films and fragments may be more closely related to runoff, packaging, agricultural plastics, and degraded plastic waste. Karst systems can therefore act both as rapid transport pathways and as temporary storage environments.

These findings show that MP management should focus on the whole catchment rather than only on spring outlets or cave entrances. Protection should include recharge areas, ponds, swallow holes, inflowing rivers, settlements, agricultural land, mines, tourist sites, and waste-disposal areas. The COCKPIT-PLUS approach may provide a useful framework for linking pollution sources, transport pathways, and groundwater targets (Haryono et al. 2023). Future monitoring should include both water and sediment, cover dry and rainy seasons, and, where possible, include sampling during rainfall events. This study provides an initial baseline for including emerging particulate contaminants in tropical karst groundwater protection.

5. Conclusions, limitations, and future research directions

This baseline study shows that suspected microplastics (MPs) are widespread in tropical karst groundwater across Java. They were visually identified in all water samples from 25 locations in seven karst areas, with abundances of 26–78 particles/100 mL. These findings indicate that karst aquifers are not fully protected from surface-derived particles because fractures, sinkholes, caves, underground rivers, and conduits can provide rapid pathways into groundwater. Their distribution appears to reflect both surface activities and karst hydrogeology. Fibers dominated most water samples and were found across different land uses, outlet types, and karst-development stages. They may come from domestic activities, laundry, textiles, household waste, and atmospheric deposition. Fragments and films may be linked to more local sources, including agricultural plastics, packaging, degraded hard plastics, mining activities, and runoff from allogenic recharge areas.

Both springs and underground rivers contained suspected MPs. Underground rivers mainly represent active transport through conduit systems, whereas springs may collect particles from wider recharge areas. Therefore, MPs found at springs may reflect catchment-scale pollution rather than only contamination near the outlet. Their occurrence across different karst settings also shows that vulnerability is not limited to highly developed conduit systems.

Suspected MPs were also found in all sediment samples, with abundances of 41–211 particles/5 g. Sediments contained more fragments and films than water samples, suggesting that water reflects active transport, while sediment records longer-term deposition and temporary storage. Some stored particles may be released again during rainfall or high-flow events.

FTIR analysis showed that most examined particles were synthetic polymers, mainly PE, PP, polyamide/nylon, PET, and EVA, while some were anthropogenic cellulosic fibers. This confirms that visual identification alone may overestimate synthetic MP abundance. Overall, MP occurrence appears to be influenced by human activities, tropical rainfall, rapid recharge, strong surface–subsurface connectivity, and sediment storage.

This study represents conditions only at the time of sampling, and repeated seasonal sampling was not conducted. Source identification also remains tentative, and FTIR was applied only to a subset of particles. Future studies should include dry- and rainy-season sampling, rainfall-event monitoring, discharge measurements, tracer tests, and broader polymer confirmation using micro-FTIR or Raman spectroscopy. For practical monitoring, both water and sediment should be sampled. Management should also focus on recharge-area protection, waste control, agricultural plastic use, and the protection of springs and underground rivers used by local communities..

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author contributions

Tjahyo Nugroho Adji: Conceptualization, Methodology, Fieldwork, Formal analysis, Writing – original draft, Supervision, Funding acquisition. Eko Haryono: Conceptualization, Methodology, Supervision. Junbing Pu: Conceptualization, Supervision. Fengling Gan: Supervision. Nor Muhamad Iskandar: Writing – original draft, Fieldwork, Formal analysis, Visualization.

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Competing interests

The authors declare that they have no competing interests.

Clinical trial number: not applicable

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