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Assessment of microplastic abundance and anthropogenic contaminations of spring water in Merapi Volcano's spring belt

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ABSTRACT

Springs are important freshwater supplies for communities, however, the spring water quality is increasingly threatened by growing anthropogenic pressures. Many springs in the Merapi spring belt are primarily allocated as recreation spots, although a number of them remain utilized by local communities for freshwater fisheries, irrigation, and even drinking purposes. This study assessed the physicochemical characteristics (pH, TDS, EC, nitrate, DO, COD, and Fe) and microplastic contamination of seven volcanic springs in Klaten Regency, Indonesia. Microplastics were identified using the NOAA microscopic method and quantified through abundance and pollution load index (PLI), while water quality data were analyzed using descriptive statistics and hierarchical cluster analysis. Most parameters complied with WHO guidelines and Indonesia's Water Quality Standards (Government Regulation No. 22 of 2021, Class I). However, elevated pH and nitrate concentrations in several springs (e.g., Jolotundo, Pelem, and Duda) indicate anthropogenic influence. Cluster analysis grouped these springs into three categories, where Tirto Mulyono and Brondong had the closest similarities in water quality due to natural conditions and human activities. Microplastics were present in all samples (n = 217 particles) with a mean abundance of 332.42 particles/L, predominantly fibers (71.89%), films, and fragments occurring in smaller proportions. Particle sizes ranged from 0.1 to 3 mm and 0.05 to 3 mm, respectively. Principal component analysis suggests that contamination is linked to localized human activities such as recreation and domestic use. CF values (1–3) and PLI (>1) indicate moderate contamination. These findings highlight the vulnerability of volcanic spring systems to microplastic and nutrient pollution, emphasizing the need for improved management, source separation, and infrastructure development.

Keywords: anthropogenic contamination, microplastics, risk assessment, spring, water pollution.

INTRODUCTION

Springs are an essential source of freshwater for many communities, supplying water for domestic, agricultural, and recreational purposes. (Rajan et al., 2025). They form where groundwater naturally emerges at the land surface, usually when a saturated aquifer intersects geomorphological features such as hillslopes, valley floors, or exposed geological formations, enabling water to flow out from the water table (USGS, 2019). As key discharge points of groundwater systems, springs are important nearby nodes for maintaining local hydrology and ecosystem services. At the same time, their accessibility and direct link to human activities make them highly vulnerable to environmental degradation and pollution caused by humans (Ako et al., 2012; Kiwanuka et al., 2022). Groundwater represents 30.1% of the world's freshwater resources and is being increasingly put under great levels of stress because of anthropogenic contamination arising from climate change and a variety of human activities. The flow of groundwater to springs occurs in unconfined aquifers that have unsaturated layers at the top. Topography also plays a major role in the direction and slope of groundwater flow (Setiawan et al., 2019).

Springs in the Merapi Volcano area are utilized for fulfilling domestic needs, agriculture, and other economic sectors in its lower slope area. Genetically, the spring occurs in this area because it is situated in a break-of-slope area with loose volcanic material, which makes water easily emerge to the surface as springs (Ratih et al., 2019). These types of springs belong to depression and artesian springs with high and continuous flow rates. However, with the increased human activities both in recharge areas and the surroundings of the catchment, the degradation of water quality may appear, which could involve the emergence of chemical pollutants or new kinds of particles such as microplastics. With the development of residential areas, intensive agriculture, small industries, and tourism around springs, anthropogenic pressure on the hydrogeological environment has significantly increased. Parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), nitrate, and chemical oxygen demand (COD) may be the key indicators assessing the influence of human activities on water quality. Besides, microplastic pollution is persistent and has the potential for long-term impacts on human health and ecosystems, which may also originate from anthropogenic activities around the spring (Bao, 2025).

Besides, research on microplastics in Indonesia has been done widely in the sea and rivers (Lestari et al., 2020; Isfarin et al., 2024). However, research related to microplastics in spring water is still limited. A few studies have looked into the quality of volcanic springs in Klaten with an approach that combines waste indicators of domestic pollution, such as pH, DHL, TDS, nitrate, and COD (Infusino et al., 2022), with microplastics as new parameters. Therefore, determining the conditions of water quality in the seven volcanic springs of the study area and the degree to which anthropogenic activity affects these parameters becomes necessary. Moreover, information on the abundance and characteristics of microplastics in each spring is of paramount importance in understanding the potential environmental risks (Yanuar et al., 2023).

A number of studies have evaluated the quality of springs in volcanic areas in Indonesia, showing variations in characteristics and levels of pollution. Isotopes analysis at Umbul Wadon, Sleman, was successfully conducted to identify the origin and recharge zone of the groundwater flow from some surrounding areas (Wijatna et al., 2013). Meanwhile, nitrate concentrations in the groundwater and springs were observed to be relatively higher in areas with livestock and residential functions compared to forested areas in the District of Cangkringan, Sleman, and were suspected to be influenced by anthropogenic activities in altering the water quality of the aquifer (Zahidah et al., 2025). A spring water sample generally met the drinking water quality standard as stipulated by WHO, though several parameters, such as pH and fecal coliform levels, exceeded the permissible limits in Baturiti Village, Tabanan (Suryaputra et al., 2021).

The objectives of the study are: (1) to analyze the impact of anthropogenic activities on spring water quality and (2) to assess the abundance and risk evaluation of microplastics found in the seven volcanic springs. This research is expected to give an overall picture of volcanic water quality in the Klaten area, shed light on human activities on the spring water, and provide preliminary evidence of the existence and distribution of microplastics in spring water.

MATERIAL AND METHODS

Study area

The study area is located on the eastern slope of Mount Merapi in Klaten Regency, Central Java. The seven investigated springs are situated within a spring belt on the volcanic lower floodplain (Figure 1). According to the geological and hydrogeological reconstruction of the eastern slope of Mount Merapi by Selles (2014), this series of springs is classified as *Spring Belt 2*. The spring belt on the volcanic footplain exhibits distinct characteristics compared to the one located at higher elevations (*Spring Belt 1* on the volcanic foot morphology). Springs within the volcanic floodplain belt on the slopes of Mount Merapi are characterized by a high discharge, reaching up to 1.000 L/s.

In general, the spring that occurs because of the curvature of the slope shape constitutes a spring belt called depression springs. The spring flows gravitationally due to the interaction of the groundwater level and the surface of the land

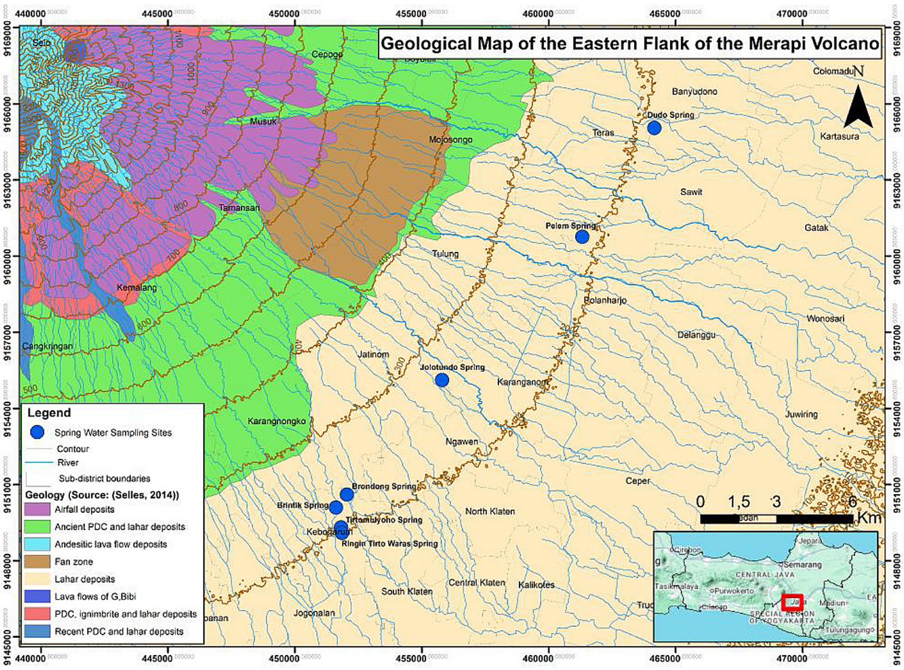

Figure 1. Geological setting and sampling sites

(Todd, 1980). Additionally, in the hydrogeological study of Selles (2014), Pelem and Jolotundo Springs have been categorized as fault contact type of spring. The reason behind the spring's occurrence might be the continuous underground impermeable structures represented by the fault. Springs of the type of fault contact mostly come from the confined aquifer, which discharges the water artesianly (Todd, 1980). This type of spring has a larger flow rate compared to others situated in the eastern flank of Merapi (Selles, 2014).

Sampling procedures

Spring water samples were collected using the grab sampling technique at randomly selected spring reservoirs. To ensure the representativeness of the groundwater, samples were taken directly from the upwelling zone (spring eye) where the water emerges under artesian pressure. At each site, pH, electrical conductivity (EC), total dissolved solids (TDS), and temperature were measured in situ by submerging a calibrated multi-parameter water checker tester (PCS Testr 35) which has been calibrated in the laboratory Samples for nitrate and microplastic analysis were collected in 1-liter bottles submerged at a median depth to avoid surface film contamination.Specifically, microplastic containers were pre-rinsed with filtered distilled water to maintain sample integrity. Samples for chemical oxygen demand (COD) were collected in 500 mL bottles and immediately acidified with concentrated H_2SO_4 to pH < 2 for preservation. In total 21 sampel for 7 springswere stored in a portable cool box at 4 °C during transport to the laboratory. The sampling protocols followed standard methods for water examination (APHA, 2022). The sampling locations are presented in Figure 1.

Water quality analysis, microplastic analysis, and statistical analysis

Water quality parameters (pH, EC, TDS, COD, and nitrate) were evaluated in accordance with the WHO Guidelines for Drinking Water Quality (2022) and Indonesia water quality standard (WQS) on Government regulation No. 22 of 2021 of Class I to assess their suitability for human consumption. Microplastic characteristics (shape, color, and size) were visually identified using microscopic analysis following NOAA protocols (Masura et al., 2015) using Olympus Research Microscope Model Bx53 Trinocular Phase These parameters were selected to support the identification of potential pollution sources and to differentiate between geogenic and anthropogenic influences. Statistical analysis of the spring water quality was conducted using OriginLab software, to perform multivariate techniques and characterize pollutant dynamics. Principal component analysis (PCA) was utilized to represent the relationship between microplastic characteristics (shape and type) and their potential sources, effectively reducing the complexity of the dataset into principal components that explain the variance in water quality (Ako et al., 2012).

Spearman correlation was applied to identifying associations between non-normally distributed data, such as microplastic counts and chemical concentrations (Nazir et al., 2024). Furthermore, Hierarchical Cluster Analysis (HCA) and Heatmaps were used to categorize sampling locations and parameters based on statistical similarity. This spatial clustering helps isolate hotspots of contamination and differentiate between natural geogenic baselinesand anthropogenic inputs, such as those originating from tourism or agricultural runoff (Ako et al., 2012; Nazir et al., 2024). Descriptive statistical analysis (mean ± standard deviation) was applied to all parameters based on triplicate measurements, as this study focuses on parameter characterization rather than inferential statistical relationships.

Microplastic risk assessment

Microplastics abundance

The abundance of microplastics in the samples was calculated based on the number of particles per liter for water samples and the number of particles per kilogram (dry weight) for sediment samples, as shown in Equation 1.

$$\text{Microplastic abundance (particles/ L)} = \text{(Number of microplastic particles/ weight of sediment sample (L)} \quad (1)$$

Pollution load index (PLI)

The pollution load index (PLI) is calculated to evaluate the microplastic load compared to the background level in each sampling site. The PLI was estimated using the following formulas (2) and (3) below.

$$Cf_i = C_i / C_{oi} \quad (2)$$

$$PLI = \sqrt{CF_i} \quad (3)$$

where: denotes the ratio between the microplastic (MP) concentration at a given site (C_i) and the background MP concentration (C_{oi}). The background concentration is defined as the minimum MP level detected among all sediment samples (Lim et al., 2024; Nazir et al., 2024). *CF* values are grouped into four levels: $CF < 1$ denotes low contamination; values between 1 to 3 indicate moderate contamination; those ranging from 3 to 6 represent considerable contamination; and $CF > 6$ signifies a very high degree of contamination. Meanwhile, *PLI* exceeding 1 is considered polluted.

RESULTS AND DISCUSSION

Characteristics and potential anthropogenic pollution in the spring water

The WQPs results for seven springs are represented in Table 1. The WQPs for these springs generally comply with the WHO drinking WQS for pH, total dissolved solids (TDS), electrical conductivity (EC), nitrate, and iron (Fe). However, pH and nitrate concentrations in the Jolotundo, Pelem, and Duda springs slightly exceed the WHO WQS. The observed pH values, which range from 6.73 to 9.7, indicate alkaline conditions that may result from both natural processes and human activities. Natural processes are also influenced by aquifer conditions, namely water retention time and lithological settings (Rajan et al., 2025; Rani et al., 2020). Meanwhile the Nitrate were value for Jolotundo, Pelem and Duda are 17.96, 15.14, and 22.26 mg/L repectively, is similar which research conducted in Saarland Germany with the mean nitrate value 30 mg/L influence by agriculture (Weber and Kubiniok, 2022). Figure 2 demonstrates a strong correlation between nitrate and pH (r = 0.96), potentially associated with local land use. The nitrate concentrations range from below 0.03 mg/L to 22.26 mg/L. The highest were found in Duda Spring, which is closely related to settlement and vegetation, such as trees, and agriculture.

As indicated in Table 1 and Figure 3, land use within the 10-meter buffer zone surrounding the springs is primarily settlement, vegetation, and toilet facilities. Additionally, most springs are used for swimming between 07:00 and 16:00, and sampling was conducted during this timeframe. In Indonesia, the disparity of pH in the volcanic spring water is 6–9. Selles (2014) estimated the pH of springs on Mount Merapi's eastern slope to range between 6.2 and 8.6 by conducting surveys during the dry season. According to Setiawan et al. (2019), the pH on the southern slope of Mount Rinjani ranged within 6.3–6.8 for these springs. Irawan (2009) found that on Mount Ciremai, a pH range of 6.15 to 9 was recorded from measurements at 119 different spring sampling points. Nitrate concentrations in springs have generally been studied for seasonal variations, but pH may vary on a diurnal basis. However, diurnal variation in nitrate also exists and is biologically mediated or in relation to light, temperature, and pH fluctuations (Heffernan and Cohen, 2010; Aubert and Breuer, 2016). Meanwhile, COD values ranged from 10 to 22 mg/L, with 62.5% of samples exceeding the Indonesian Water Quality Standard (Class I: 10 mg/L). Only Tirto Waringin and Brintik Spring met the standard. Observed peaks of 19–22 mg/L indicate the presence of episodic or localized pollution sources rather than natural background conditions.

EC and TDS exhibited a strong correlation (r = 0.99). Both parameters remained below the acceptable limits established by the World Health Organization Water Quality Standards (WHO WQS), with EC ranging from 228 to 474 µm and TDS from 113 to 237 mg/L. The spatial distribution of TDS and EC values displayed a distinct pattern. As illustrated in Figure 1, the springs are aligned from southwest to northeast, extending from Titro Mulyono to Duda spring, and both EC and TDS values progressively increase toward the east. The EC and TDS values measured in these springs are lower compared to those reported in other springs (Infusino et al. 2022; Shrestha et al., 2023). Furthermore, EC and TDS show a strong positive correlation with nitrate concentrations. The Spearman correlation coefficient between EC and nitrate is 0.73, and between TDS and nitrate is 0.78, respectively, showing a relation with other similar results (Rawat and Joshi, 2019)

The heavy metals parameter Iron (Fe) was also identified at a low concentration and below the WHO WQS. Similar results of Fe have been reported in other spring systems, with measurements showing Fe content of 0.04 mg/L in hot spring water samples in Tubbe Village, East Nusa Tenggara (Karbeka et al., 2020). According to the Spearman correlation in Figure 2, Fe

Table 1. Water quality result

Parameters	Unit	WHO quality standards	Indonesia WQS Class I	Tirto Mulyono Spring	Tirto Waringin Spring	Brintik Spring	Brondong Spring	Jolotundo Spring	Pelem Spring	Duda Spring
Temperature	°C	-	-	24	24.2	25.5	25.4	23.2	23.1	24.9
PH		6.5–8.5	6–9	7.2	8.03	7.06	6.73	9.61*	9.5*	9.7*
TDS	mg/L	600	1000	113	117	117	144	152	231	237
EC		750	-	228	234	232	294	303	461	474
DO	mg/L		6	5.92	5.24	5.41	5.58	5.07	6.93	5.41
COD	mg/L		10	19.50*	10.00	10.00	19.00*	12.50*	10.50*	22.00*
Nitrate	mg/L	10	10	4.65	4.90	< 0,03	2.63	17.96*	15.14*	22.26*
Fe	mg/L	0.3	0.01	0.06	< 0,01	0.04	< 0,01	< 0,01	< 0,01	0.05
Water utilization				Swimming, drinking water from different pipes	Swimming, washing clothes	Swimming and drinking water in the same pool	Swimming	Swimming, fishpond	Swimming	Swimming
Spring typology				Depression spring	Depression spring	Depression spring	Depression spring	Fault Contact (Selles, 2014)	Fault Contact (Selles, 2014)	Artesian spring (Simoen, 2001)
Non-point sources in a 10 m buffer area				Settlement Rice field Restaurant Swimming pool Shower room/toilet Parking area/empty land	Settlement Rice field, Restaurant, Swimming pool Bush	Swimming pool, Vegetation, empty land/ parking area	Restaurant, swimming pool, Bush, Vegetation, wetland	Settlement Swimming pool Bush Vegetation Empty land/ parking area	Settlement Swimming pool Bush Vegetation Empty land/ parking area Shower room/toilet	Settlement Swimming pool Vegetation Empty land/ parking area

Note: *Exceeding the WHO water quality standard.

was not correlated with any other parameter, with the strongest correlation found between COD and Fe (r = 0.58). The low concentrations of Fe are more likely related to rock and water interactions, that is, with alluvial deposits coming from Merapi volcanic sediments without considerable contributions by anthropogenic contaminants. Moreover, although dissolved oxygen and chemical oxygen demand are not included as drinking water parameters, both can be indicators of pollution from anthropogenic sources, together with nitrate. The COD values were above the Indonesian Water Quality Standards under Government Regulation No. 22/2021 for Class I waters, with a COD limit of less than 10 mg/L. This means that such activities as swimming, restaurants, and laundry in several springs might be among the contributory factors to the high values of COD. In contrast, DO values were still within the limit.

A hierarchical cluster analysis (HCA) was applied to understand the linkage between springs and to identify similar water quality characteristics (Shrestha and Kazama, 2006). The dendrogram in Figure 4 presents the clustering of 7 sampling sites into 3 groups. Cluster 1, comprising Tirtomulyono spring and Brondong spring; Cluster 2, comprising Tirto Waringin spring and Brintik spring; and Cluster 3, comprising Jolotundo spring, Duda spring, and Pelem spring, are the three clusters that demonstrated the most similar hydrochemical characteristics. The pollution influence of Jolotundo spring clearly separates from the other clusters, characterized by higher EC, TDS, nitrate, and COD, hence showing stronger anthropogenic influences caused by domestic activities and swimming. The spatial position of

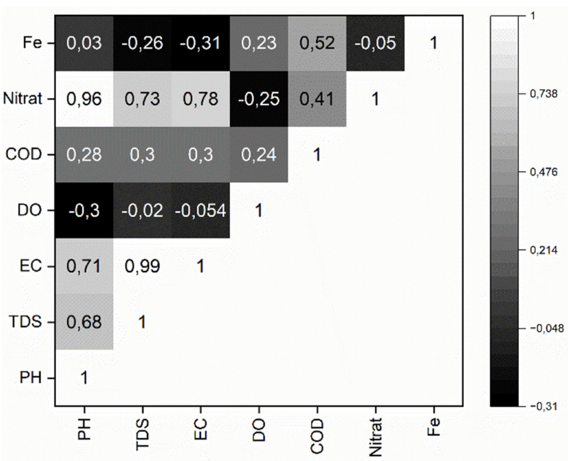

Figure 2. Spearman correlation of all water quality parameters.

these springs in the eastern part of the catchment aligns with the increasing trend observed in EC and TDS. Overall, the HCA did support the previous results, it was shown that variability in water quality is controlled by natural hydrogeological settings and variable land-use pressures.

Microplastic analysis

Microplastic abundance, shape, and colour distribution

Microplastics were detected in all samples collected in this study. The large number of fibers detected in the water suggests that the primary source of microplastics likely originates from textile fibers released during swimming, including laundry. The examples of microplastic shapes, such as fibers, films, and fragments, are given in Figure 5. A total of 217 microplastic particles were found in spring water from seven sampling sites, displaying seven different colours such as yellow, transparent, purple, green, brown, blue, and black, as illustrated in Figure 6. Meanwhile, the microplastic shapes identified were categorized into three shapes: fibers, films, and fragments. In the water samples, a total of 144 transparent fibers were detected, and most of the coloured microplastics (yellow, purple, green, brown, and blue) were fibers. Fibers are reported as the most widespread of microplastics in the freshwater (Pathan et al., 2025).

The abundance of microplastics ranged from 210 to 480 particles/L. Microplastics in spring water varied in size, however, in this study, they were generally classified into two size categories: 0.05–0.1 mm, which accounted for 49% of the total particles, and 0.1–3 mm. Smaller-sized microplastics (0.05–0.1 mm) were dominant in Tirto Waringin, Brondong, and Pelem springs, while larger-sized particles (0.1–3 mm) were dominant in Tirto Mulyono, Brintik, Jolotundo, and Duda springs. These findings are consistent with microplastic size distributions reported for other spring systems (Yanuar et al., 2023). In river environments, microplastics are typically smaller, generally <0.5 mm (Amrutha et al., 2022; Lim et al., 2024). Examples of microplastic shapes, including fibers, films, and fragments, are shown in Figure 5.

Potential pollution sources of microplastics

Based on the microplastic shape, color, and size analysis, it is indicated that the characteristics

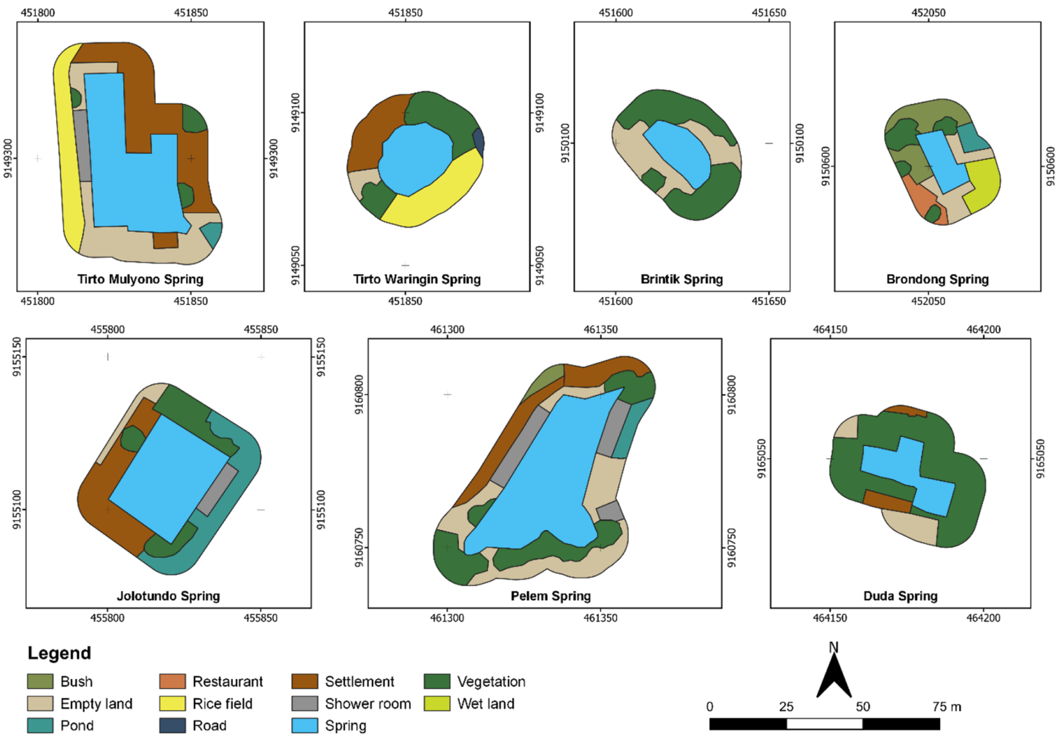

Figure 3. Non-point source pollution in a buffer of 10 m from anthropogenic activities

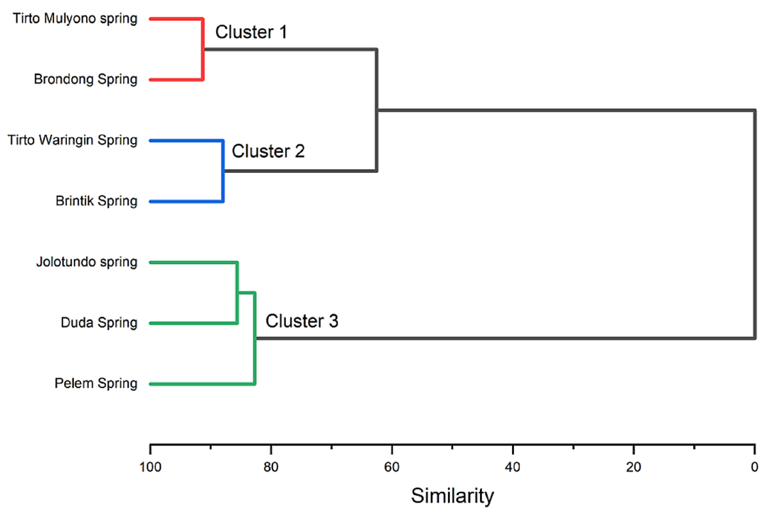

Figure 4. Hierarchical cluster analysis dendrogram showing spring water quality parameters similarity

assist in identifying the potential sources of the particles. Black fragments of different sizes were identified in all spring locations, as shown in Figure 7. These black fragments are likely from the degradation of rubber tires or synthetic materials released during swimming activities. This observation is further supported by the PCA in Figure 8. The variances explained by PC1 and PC2 were 41.17% and 23.74%, respectively, which accounted for 64.91% of the overall variability in microplastic characteristics across the sampling sites. Indeed, Springs Brintik and Jolotundo loaded strongly on PC1, with these sites being dominated by microplastic items such as blue fragments, yellow films, and brown fibers. On the contrary, Tirtomulyono and Brondong loaded more strongly on PC2, reflecting the influence of fiber types, especially colorful fibers like yellow and purple fibers, representing the secondary sources of variation. This separation of the spring catches the distinct contamination patterns of mainly transparent films, dominant in

Figure 5. Representative microplastic types observed at the sampling sites: (a) fiber, (b) film, and (c) fragment

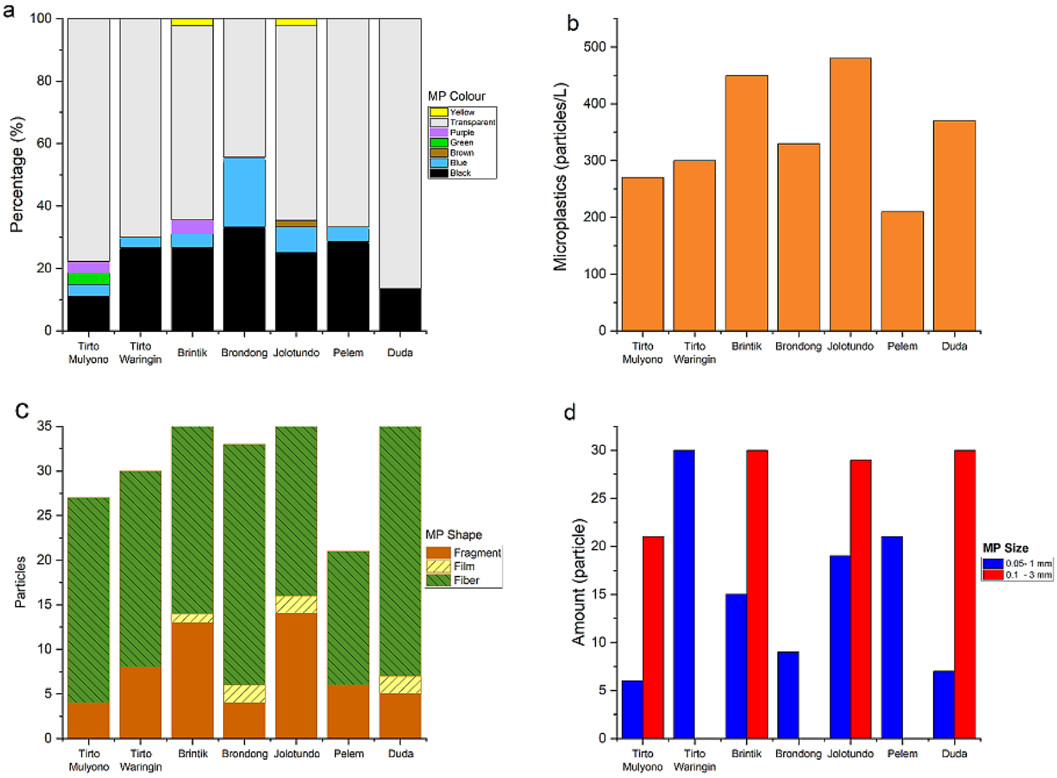

Figure 6. Characteristics of microplastics from seven spring water samples in Merapi Volcano's spring belt, Klaten Regency. (A) Microplastic colour. (B) Microplastic abundance. (C) Microplastic shape. (D) Microplastic size

Brintik, and green fragments in Jolotundo. Such a pattern indicates that microplastic contributions were mainly related to land use (Gonzalez-Saldias et al., 2024) and associated with the localized activities, such as swimming, laundry, domestic uses, or material degradation.

Microplastic pollution load index (PLI)

The contamination of microplastics was assessed using CF and PLI to evaluate the risk of contamination in the spring water. The CF value varied distinctly among these springs for all sampling sites, ranging from 1 to 3, and was classified as 'moderately contaminated'. Among those seven springs, the highest CF was recorded at Jolotundo and Brintik springs, with the CF values 2.3 and 2.1 as shown in Figure 9, respectively. In contrast, the lowest CF was found in Pelem spring with the CF = 1. This result was considered high for spring water. Compared to microplastic CF in lake surface water (Pathan et al., 2025) and ocean surface water (Paray et al., 2025) in Bangladesh, this value is similar. This condition is not ideal for aquatic environments, as spring water is generally characterized by minimal contamination. High CF could be linked to recurrent human activities at these locations, such as swimming, domestic water use, and the degradation of materials commonly discarded in these locations, including rubber tires.

Correspondingly, the PLI values for all springs exceeded 1, ranging from 1 to 1.5 (Figure 9), classifying them as 'slightly polluted' (Shen et al., 2025). Research on PLI in spring

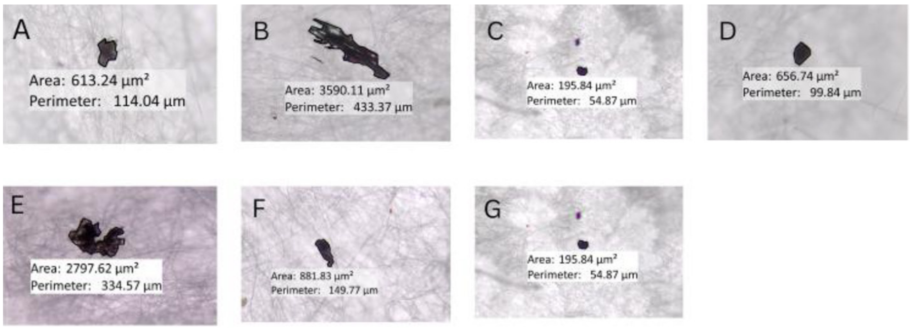

Figure 7. Black fragment found in each spring (a) Tito Mulyono, (b) Tirto Waringin, (c) Brintik, (d) Brondong, (e) Jolotundo, (f) Pelem, (g) Duda

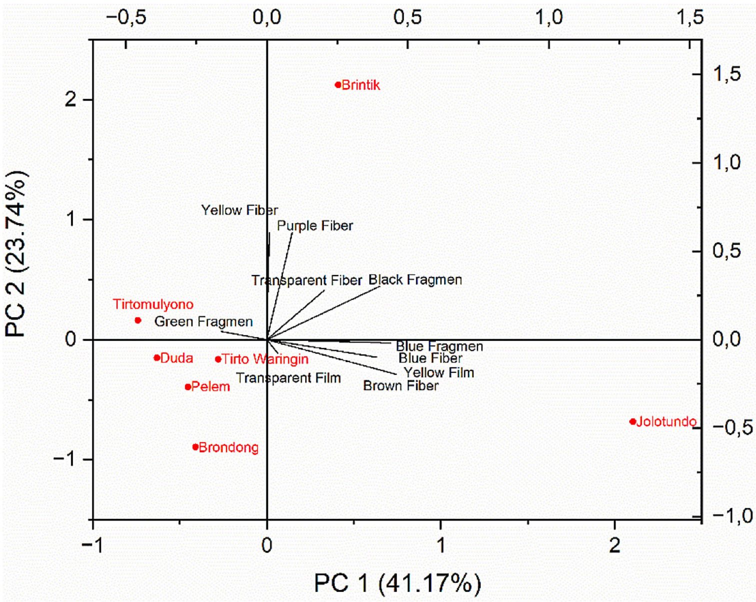

Figure 8. Principal component analysis of microplastics shape and their amount

water remains limited. Notably, compared with a study conducted on a river in Malang, Indonesia (Bahrudin et al., 2025), the level of microplastic contamination observed here is slightly lower. High PLI values were especially pronounced for the Jolotundo and Brintik sites, consistent with their high CF values and reflecting greater contamination pressures. The combined results of CF and PLI indicate that a spring with a higher degree of human use tends to reveal higher microplastic pollution, hence pointing out the role of localized anthropogenic stressors in shaping the levels of contamination.

Implications of this study

The seven spring waters serve as a crucial water resource in Klaten Regency. Among seven springs, two springs, namely Brintik and Brondong spring, are often utilized as a drinking water supply by local communities. Moreover, most of the springs were used for swimming and other domestic purposes. Therefore, ensuring the safety of drinking water for communities is essential. One possible approach is to reduce the use of plastic materials in spring environments, such as plastic floats, repurposed rubber tires, and food packaging, which contribute to microplastic inputs. It is also important to raise community awareness about avoiding the consumption of spring water taken from the same pools used for swimming. In addition, in Jolotundo spring, the water from the reservoir is also utilized for freshwater fisheries. A good example comes from Pelem Spring, which has already implemented separation between the main spring source with the swimming area. This practice will minimize microplastic contamination in the spring water.

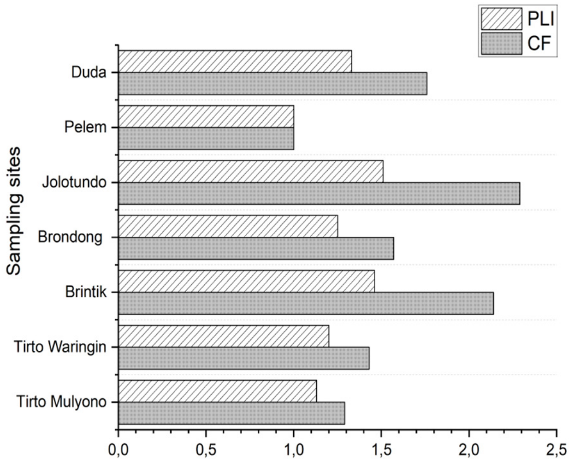

Figure 9. Contamination factor (CF) and pollution load index (PLI) of microplastics in seven spring water

Moreover, focusing solely on microplastic abundance and associated chemical hazards may underestimate their broader ecological implications. However, there was no significant correlation between water quality concentration in the tested water sample and microplastic abundance in the sampling sites.

CONCLUSION

This study assessed microplastic and anthropogenic contaminants in the seven springs of the Merapi spring belt in Klaten Regency, thus contributing to the global knowledge gap concerning emerging pollutants in water resource systems. Notably, several springs exhibited elevated pH and nitrate concentrations, namely Jolotundo, Pelem, and Duda springs, which indicate anthropogenic contamination from swimming activities, restaurants, and domestic sources. Anthropogenic contaminations can also be identified from high COD values in almost all springs. Moreover, cluster analysis has classified the spring water quality characteristics into three clusters. Microplastics were detected in all springs (210–480 particles/L), with higher abundances at Jolotundo and Brintik. Fibers dominated (71.89%), followed by fragments and films, with sizes primarily between 0.05 and 3 mm, indicating sources related to domestic wastewater, clothing fibers, and recreational materials. Multivariate analysis (PCA and cluster analysis) identified spatial variability and confirmed the linkage between land use and contamination patterns.

The PCA underscores that these microplastic particles likely originated from clothing fiber, swimming floats from black rubber tire, and other materials from domestic of restaurant waste in the surrounding spring area. The risk assessment from the CF and PLI indices classified all springs as moderately contaminated and slightly polluted. The contamination factor (CF = 1.58) and pollution load index (PLI = 1.26) classify the springs as moderately contaminated and slightly polluted, highlighting increasing anthropogenic pressure on systems typically considered pristine. These findings emphasize the ecological and water resource implications of emerging pollutants in spring environments. Effective management should prioritize source control through improved sanitation, separation of recreational and drinking water zones, and strengthened public awareness to ensure long-term sustainability of these critical water resources. These research findings can be used for policymakers to improve infrastructure to separate drinking-water sources from swimming areas, and raising public awareness is critical step to ensure the long-term protection of these spring ecosystems.

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