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Quantitative analysis of microplastic presence in commercially bottled drinking water brands and the associated human exposure

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ABSTRACT

The presence of microplastic contaminants in bottled drinking water has raised growing concern due to their harmful effects on both human health and the environment. In this study, we investigate the occurrence of microplastics in 17 commercially available bottled water brands in Kota Kinabalu, Sabah, Malaysia. This study also quantifies the level of microplastics based on their sizes, shapes, colors, and polymer types. The associated risk through ingestion level of microplastics in drinking water was evaluated. The quantification analyses showed that the average abundance of MPs varied from 2 ± 1 particles/L to 42 ± 1.52 particles/L with the highest number of MPs found in brand D. The results showed that MPs were detected in four distinct forms (line, fragments, fibers, and pellet). MPs particle sizes ranged from 100 um – 5000 um with 38% of particles dominant in sizes 500 um to 1000 um. Microplastics were documented in five distinct colors, with black representing 48% of the total count. Infrared spectral analysis (FTIR) confirmed that the occurrence of high polypropylene (PP) polymers in bottled water primarily originate from the packaging materials and bottle caps. The estimated daily intake of microplastics (EDI) by children and adults was determined to be 0.53 and 0.19 particles/kg/day. These findings offer crucial data for a more in-depth assessment of the potential health risks linked to human exposure to microplastics.

Keywords: *Drinking water bottles, Microplastics, FTIR analysis, Human exposure*

1. INTRODUCTION

Microplastics are defined as small pieces of plastic, smaller than 5mm, originating from different sources which come in a variety of shapes and colours [1]. In Malaysia, the production and consumption of plastics have seen a dramatic increase since 1950 [2]. In 2020, it was reported that the annual household plastic packaging showed a significant amount of consumption particularly in the food and beverage sectors, where demand surged due to the Covid-19 pandemic [3]. However, the downside of this growth lies in the poor management of plastic waste and litter from land-based sources, which has led to an increased influx of microplastics into the environment. It was reported that nearly 50%, equivalent to approximately 0.4 million tons of Malaysia's plastic waste is discharged into aquatic environments [4]. These pollutants occur in varying concentrations across multiple sources, including marine waters [5], wastewater, freshwater systems, food, air, and both bottled and tap water. Furthermore, microplastics have been detected in a range of food products, with their presence also confirmed in human stool samples. This suggests unintentional consumption of microplastics from diverse sources, raising concerns about potential adverse health effects. Considering the widespread occurrence of microplastics in food samples, there is a valid concern about their presence in bottled water sold in Malaysia. Previous studies by Cao Ngoc et al., [6], highlighted that there are numerous potential routes for microplastic contamination in bottled drinking water. Microplastics in such water sources can originate from treatment facilities, during transportation, and even from the packaging itself. The ingestion of contaminated food and water represents one of the main routes through which microplastics enter the human body, owing to their capability to absorb various types of contaminants. In accordance with the Food Regulations 1985, any party intending to distribute natural mineral water (NMW) or packaged drinking water (PDW) for human consumption or commercial use must first obtain a license for the water source from the Ministry of Health, Malaysia [7]. NMW can be sourced directly from subterranean water-bearing strata through springs, wells, boreholes, or other outlets. Typically, NMW undergoes one or more treatments such as filtration, chlorination, aeration/deaeration, carbonation/decarbonation, and ultraviolet sterilization [8]. In contrast, packaged drinking water (PDW) is generally sourced from public water supply systems or tap water, as well as surface water bodies (rivers, ponds, and lakes) and underground sources (tube wells and springs). This water undergoes additional purification process such as distillation, reverse osmosis, electrodialysis, ion exchange and sterilization before packaged as bottled drinking water [7]. NMW can be found in various colored bottle caps while for PDW usually in white colored bottle caps. To date, there is limited data on detection and identification of MPs in bottled drinking water commercially in Sabah, Malaysia. Understanding the potential impacts of MPs on human health requires research into their types, concentrations, and associated toxicity in bottled water. This study helps assess potential threats to consumer safety while addressing broader environmental concerns. Therefore, the objective of this study is to investigate and examine the occurrence and distribution of microplastics in 17 specific bottled water brands within the Sabah, Malaysian context. Additionally, this study delves into the potential sources of microplastics from NMW and PDW. Finally, this study estimates the Estimated Daily Intake (EDI) from bottled water to assess the levels of human exposure among both adults and children. The identification and characterization of microplastics in bottled drinking water not only provide valuable insights into potential exposure pathways for humans and wildlife through ingestion but also offer a deeper understanding of the implications associated with specific brands, thereby enhancing the contextual relevance of the study.

2. METHODOLOGY

2.1. Sample Collection and Preparation

A total of 51 bottled water samples comprising three independent replicates for each of 17 commercially available brands were obtained from multiple retail outlets in Kota Kinabalu, Sabah. The bottled drinking water brands were chosen based on the retail sales data to identify the top 20 brands by annual sales volume. The 17 brands of bottled water are reported to be consistently stocked across all outlets and recognized by consumers as the market leaders. Over 80 % of bottled water sales in Sabah reflect consumer purchasing patterns. Each bottle held 1,500 mL consists of bottled natural mineral water (NMW; n = 12 brands) or bottled packaged drinking water (PDW; n = 5 brands), yielding 36 NMW and 15 DPW respectively. AALL bottles were manufactured from food-grade polyethylene terephthalate (PET/PETE) and were labelled from A to Q (Table 1) to ensure traceability throughout the analytical workflow. Upon collection, samples were stored at ambient laboratory temperature (22 ± 2 °C) and processed within seven days to minimize any potential for in-bottle fragmentation or microbial growth. Figure 1 shows the methodology for sample preparation and microplastics extraction from bottled water samples.

2.2. Quality Control of the Experiments

All procedures were conducted under stringent contamination-control protocols to ensure the accuracy and reproducibility of our microplastic analyses. Prior to sample collection, each commercially bottled water container and glassware were cleansed between trials, rinsed with deionized water before use, and covered to prevent airborne particulates [1]. The filter papers were kept in a closed petri dish prior to use. This is to avoid contamination from dust or other particles which might affect the analysis [2]. To ensure high quality data, three replications are made for each brand of bottled drinking water. The blank samples (deionized water) were analyzed similar to bottled water samples. Moreover, laboratory attire is vital to ensure no other plastic material such as polyester contaminates the sample during the laboratory experiment.

2.3. Sample Filtration

The membrane filtration technique was used to separate microplastics in bottled drinking water [3]. After filtration, each filter paper was examined and photographed using a stereomicroscope (LEICA WILD M8, Switzerland) at 50× magnification, equipped with a micrometer eyepiece and a UV light attachment. Captured images were then adjusted for optimal brightness and contrast. Suspected particles on the filter paper were annotated according to their corresponding sample IDs. The physical attributes of the observed microplastic particles including size, shape (foam, fragment, pellet, fiber, and line), and color were recorded, along with specific product brand references to enhance the contextual relevance of the analysis. Then, the sample was gently transferred to a sample carrier for microplastics polymers analysis using an identified Fourier Transform Infrared (FTIR) spectrometer (Model: Brucker). The samples were scanned in 4000–450 cm−1 wave number [1]. The data was available as peaks in the spectrum generated by scans, presented as %T. The identity of a compound can be recognized from its functional groups, namely, the types of bonds between different atoms, signifying the unique arrangements of atoms and bonds that differentiate it from other compounds. The outcomes were matched using online polymer spectrum databases found in the libraries.

2.4. Assessment on Estimated Daily Intakes (EDI)

The Estimated Daily Intake (EDI) of microplastics (MPs) via bottled drinking water consumption was calculated to quantify human exposure over time. In this context, the concentration of MPs in bottled water (expressed as particles per liter, p L^{-1}) is first converted to a mass-based metric (mg L^{-1}) by multiplying the particle count by an average particle mass. The EDI (mg kg^{-1} day^{-1}) is then derived using Equation 1.

$$Estimation\ Daily\ intake\ (EDI) = (Cx\ IR)/BW \qquad (1)$$

where IR, the Ingestion Rate, is assumed to be recommended daily water intake suggested by The Malaysian Dietary Guideline 2020 (child below 8 years 1.7 L/day and adults 2 L/day; C is the mean microplastic particle in bottled water (particles/L) and BW is the body weight (kg) assumed to be 61.57 kg for adults [12]and 19.5 kg for children [13].

2.5. Statistical Analysis

The quantity of microplastics was calculated as particles/L in descriptive statistics including maximum, mean, minimum, and standard deviation, with the assumption that the samples were homogeneous solutions [3]. For morphological analysis, the number of microplastics particles, particle size, shapes, and colors across different bottled water brands was examined under optical microscope (LEICA ICC50 HD).

The microplastic abundance was expressed as the mean ± standard deviation and tabulated using Microsoft Excel. A One-way ANOVA test was employed to identify any variations in microplastic abundance.

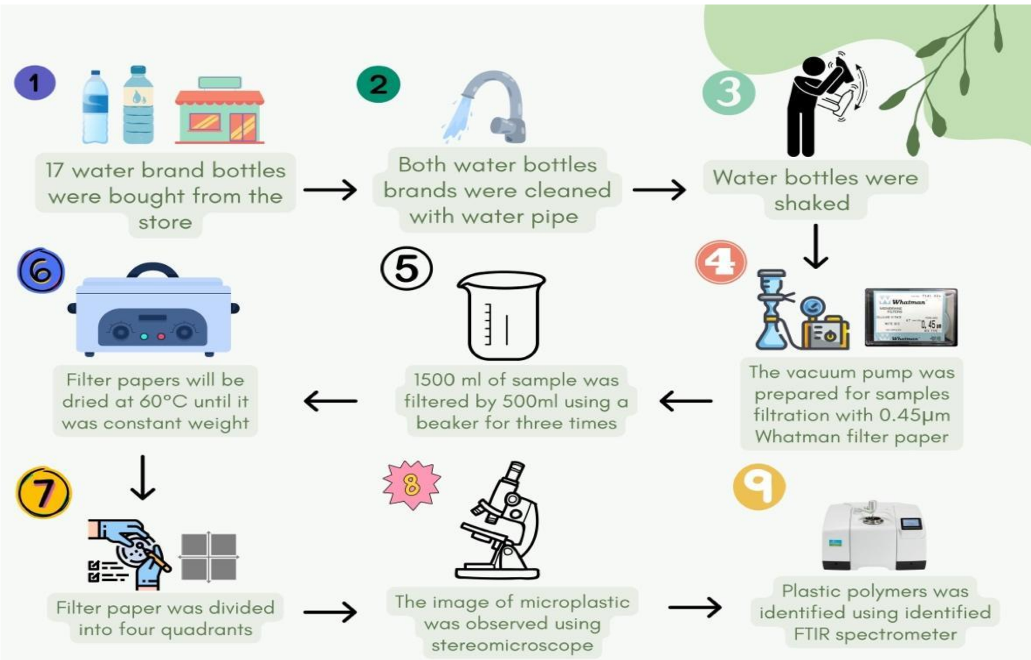


Figure. 1. The methodology for sample preparation and microplastics extraction from bottled water samples.

Table 1. General information about bottled drinking water in this study.

Brand	Cap Colour	Bottle Type	Water Type	Water Source	Expired Date
A	White	PETE	PDW	Treated pipe water	15/10/24
B	Blue	PET	NMW	Underground water	17/04/24
C	White	PET	PDW	Treated pipe water	14/11/25
D	White	PET	PDW	Treated pipe water	10/08/25
E	Blue	PET	NMW	Groundwater	18/07/26
F	Green	PET	NMW	Groundwater	08/09/26
G	White	PET	PDW	Treated pipe water	10/11/25
H	White	PET	PDW	Treated pipe water	01/10/24
I	White	PETE	PDW	Treated pipe water	10/05/24
J	White	PET	PDW	Reverse osmosis water	10/10/25
K	White	PET	PDW	Reverse osmosis water	20/03/25
L	White	PET	PDW	Treated pipe water	15/11/25
M	White	PET	PDW	Treated pipe water	10/11/25
N	Blue	PET	NMW	400ft underground reservoirs	02/04/25
O	White	PETE	PDW	Purified water	05/09/25
P	Blue	PET	NWM	Underground water	22/02/25
Q	White	PET	PDW	Treated pipe water	11/11/24

3. RESULTS AND DISCUSSION

3.1. Abundance of Microplastics in Bottled Drinking Water

The abundance and occurrence of microplastics in bottled drinking water samples for each brand was recorded in Figure 2. A total of 51 bottled water samples out of the 17 brands showed microplastics contamination with range of 2 ± 1 particles/L to 42 ± 1.5 particles/L. The average number of microplastics found in 12 bottled waters of PDW and 5 bottled waters of NMW were 6.71 and 4.86 particles/L. The mean microplastic count across all bottled water brands was (6.13 ± 1.3 items/L), with a notable variance ($p < 0.05$) observed in microplastic abundance among different water brands. Previous studies by Manson [14] reported that median concentration of 325 particles/L (range 0–10,000 particles/L) was found in U.S. bottled water. Other than that, Schymanski [15], found 1–30 particles/L in German brands when applying µFTIR imaging (20–500 µm), which more closely aligns with our PDW and NMW averages of 6.71 and 4.86 particles/L respectively. The findings suggest that certain microplastics found in bottled drinking water originate from both the packaging and the bottling process. Beyond these factors, contamination may arise from raw water sources, packaging materials, washing machines, or the process of filling water into containers. The highest number of microplastics particles was observed in brand D which had been processed with conventional drinking water treatment whereas the lowest was recorded in brand N which are raw water extracted from underground reservoirs. This may be due to differences in the raw water sources such as natural mineral and underground reservoirs which are typically pristine and untreated, whereas bottled water generally uses treated water derived from conventional drinking water treatment facilities. The presence of microplastics in bottled drinking water might originate from the handling procedures employing plastic-based equipment or pipes, like polyvinyl chloride, polypropylene, and polyethylene. It is important to note that many components in water purification and distribution systems are made from plastics such as high-density polyethylene, polyvinyl chloride, and polypropylene [16]. These materials can serve as potential sources of microplastics in the water they transport. Additionally, environmental conditions such as sunlight exposure, temperature variations, and oxygen availability play a crucial role in accelerating the degradation of plastics into secondary microplastics [17].

3.2. Physical Characteristics of Microplastic in Bottled Water

Figure 3 shows microplastic particles in bottled water were classified into four size categories: 100-500 µm, 500-1000 µm, 1000 – 3000 µm and 3000-5000 µm respectively. The results showed that no microplastics were observed under 100 µm in size. Overall, the size of microplastic recorded decreased with increasing size categories as microplastic larger than 3000 µm were the least found which only comprised 3.5% of total microplastic. Microplastic size of 500 – 1000 µm was predominant in the majority of PDW and NMW with 37% followed by size of 100 – 500 µm with 33% respectively. Previous studies reported that the distribution of microplastics size tends to be more prevalent in smaller sizes [18]. This phenomenon is likely driven by the progressive disintegration of larger plastic debris into smaller fragments through weathering, fragmentation, and degradation processes [17]. Over time, exposure to environmental factors causes these larger plastics to deteriorate, resulting in the formation of a greater number of smaller microplastic particles. A recent study conducted by Winkler et al., [19] identified mechanical stress as the primary cause of microplastic contamination in bottled drinking water. They developed a model to elucidate the pathways through which mechanical stress leads to the degradation of microplastics within a bottle [18]. Furthermore, Winkler et al., [19] suggested that the main mechanical cause of bottled water contamination arises from the release of microplastic particles originating from the bottle neck and plastic cap due to repeated opening and closing. They also investigated how bottle squeezing affects the release of microplastics in bottled water. Furthermore, Julienne et al., [20] proposed that both mechanical stress and manufacturing processes contribute to the fragmentation of microplastics.

Throughout the study, a total of five colors of microplastics were identified, black, transparent, blue, red and grey (Figure 4). Notably, black particles were the most dominant across all brands, accounting for approximately 42% of the total microplastics detected. This followed by transparent (32%) > blue (14%) > red (1.9%) > grey (1%) respectively. The high prevalence of black microplastic can be attributed from materials that may contain black pigments or dyes that have been used for packaging drinking water. During the manufacturing process, small black-colored microplastic particles can be released and contaminate the water. Apart from that, the transparent microplastics may be due to the bleaching process involving the removal of colorants and impurities from water, which can result in the loss of color from microplastic particles, rendering them transparent. Notably, previous studies on mineral water did not include information on the color of microplastic, limiting direct comparisons with our findings. Hence, this study provides meaningful insights into the color variation of microplastics found in mineral water samples, enhancing the overall understanding of microplastic pollution in aquatic ecosystems. In this study, four different shapes of microplastics (line, fragment, fiber and pellet) were observed in both PDW and NMW bottled water. Most of the detected microplastic were lined with (42%) followed by fragments (35%), fiber (20%) and pellet (4%). The maximum number of lines were found in Brand D, which comprised 22 ± 39 particles/L of line which cover 6.9% of total microplastic recovered from bottled drinking water brands. It has been shown that fragments dominated second higher morphology with the same (brand D) recorded 90 ± 39 particles/L which are 28.5%. of total microplastic found.

This finding is in line with Albert et al., [21] reported that fragments were one of the most microplastic found in drinking water samples. The breakdown of microplastics could result in a significant presence of fragment shapes within tap water samples, while fibers may potentially stem from contamination carried through the air. Research conducted by Winkler et al., [19], reported that fragment-shaped microplastic particles can be released from bottle caps, necks, and packaging materials as a result of mechanical stress during the bottling process and transportation from water manufacturing facilities. Furthermore, consumer handling actions such as squeezing, shaking, or repeatedly opening and closing bottles may also contribute to the generation and release of these fragment-type microplastics. Additionally, Additionally, exposure to heat during storage can accelerate fragmentation and increase the release of microplastics from the cap, bottleneck, and packaging materials [22]. However, our finding is in contrast with Pivokonsky et al., [23] who reported that fragments were the most common type of particle found in treated tap water samples followed by fibers and films.

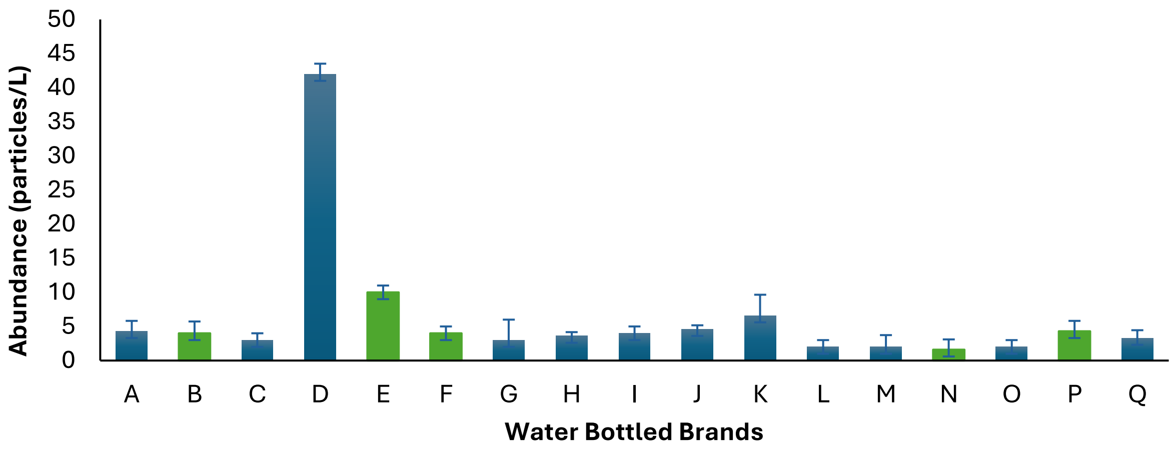


Figure 2. Abundance of microplastics found in different brands of bottled water.

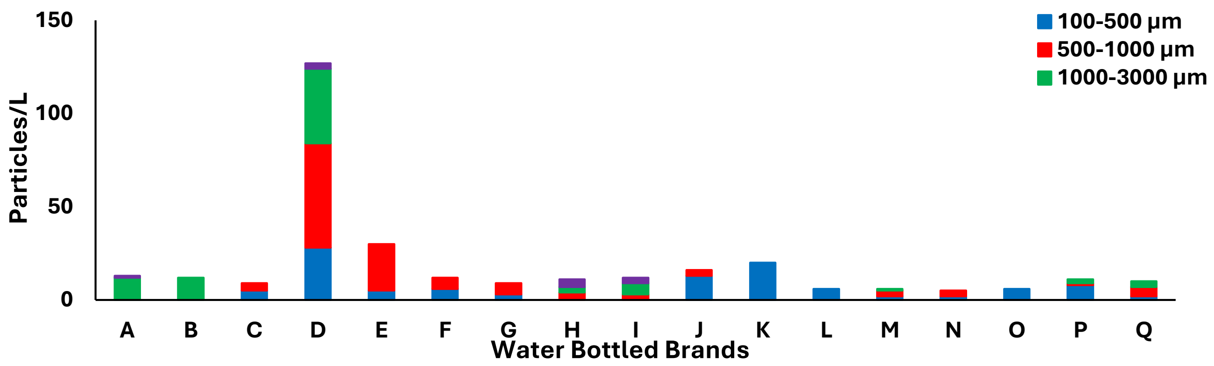


Figure. 3. Size classification of microplastics in different brands of bottled water.

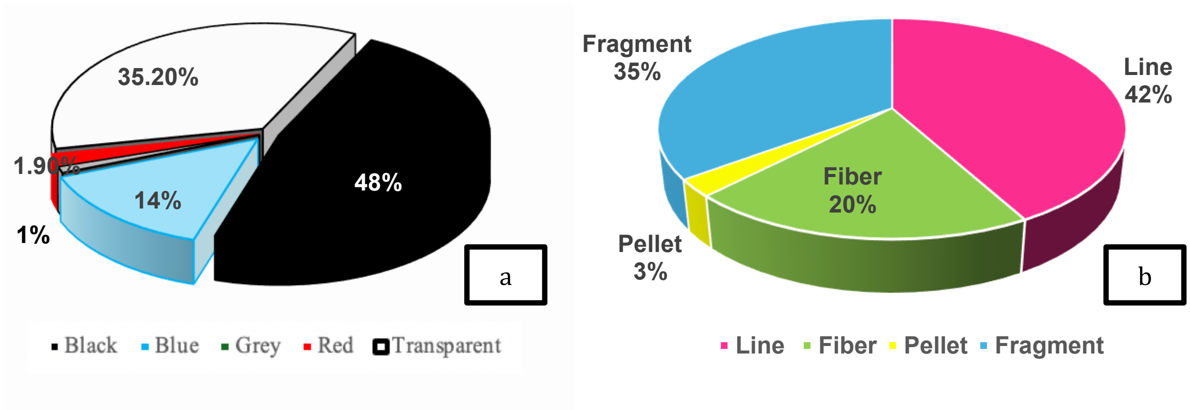
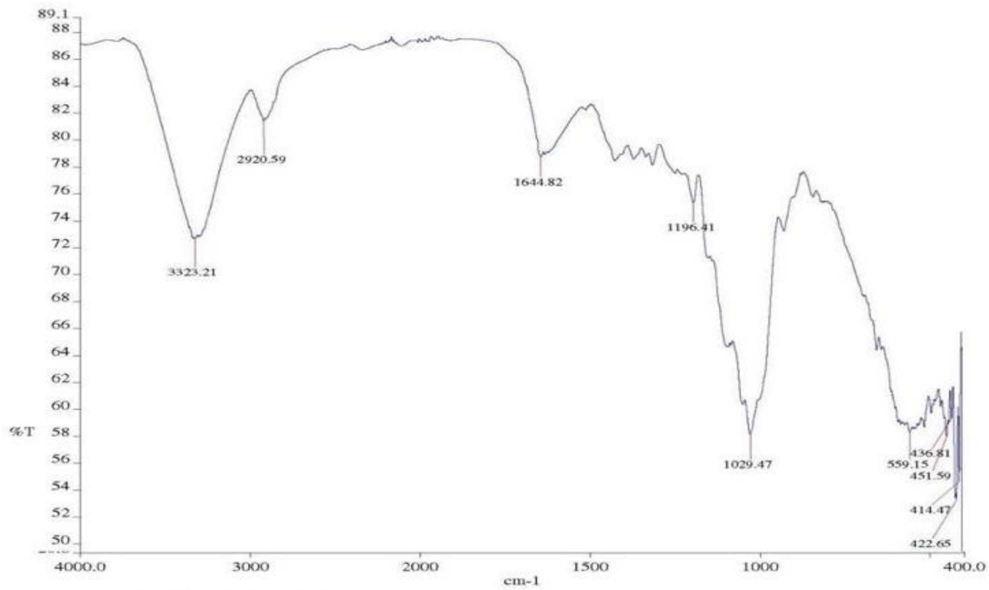


Figure 4. a) Percentage of various microplastic colors observed in different brands of bottled water and b) Percentage morphology based by shape.

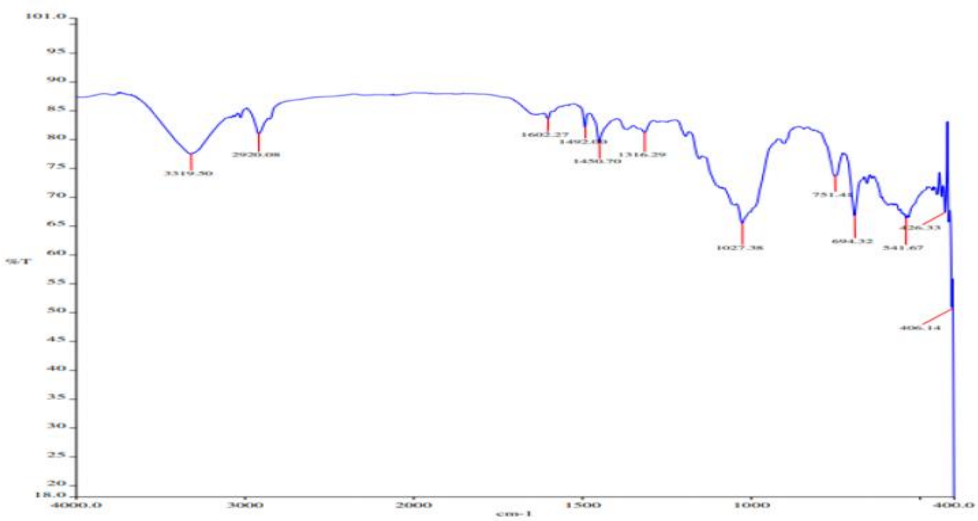
3.3. Polymer Characterization

Figure 5 presents the FTIR spectra of selected microplastics particles from 17 commercial bottled water brands. Among the identified polymers, three were detected as PE, PP and EVA. The distribution patterns of polymer type were as follows PP (65%), PE (30%) and EVA (5%). Three distinct ranges were observed: 2800- 3000 cm-1 (stretching vibrations groups of CH/CH2/CH3 groups), 1760–1670 cm−1 (CO stretching vibration), 1000- 1300 cm-1 (ester; C-O stretching) and 500- 600 cm-1 (Halo compound; N-H stretching). In this study, PP was the most frequently identified polymer in bottled drinking water which strongly supported the previous study by Kankanige & Babel, [24] reported that the most popular plastic used in bottle caps is PP. Other than that Polypropylene (PP) and polyethylene (PE) are the predominant polymers among the microplastic fragments recovered from bottled drinking water largely because these two polymers are the principal materials used in bottle fabrication and closure systems, and their physicochemical properties favor their release and persistence [14]. In most commercial bottled water systems, the bottle bodies are molded from high-density polyethylene (HDPE) or polyethylene terephthalate (PET) blends often containing PE components, while the screw caps are almost universally manufactured from PP. During the bottling, transport, and handling processes, friction, thermal stress, and mechanical wear at the bottle–cap interface liberate small PP and PE particles [15]. Furthermore, since the densities of PP and PE are both below 1 g/cm^3, these polymers tend to float. This observation aligns with Sherri et al., who reported that polypropylene (PP) is commonly used in the production of plastic bottle caps. Similarly, polyethylene representing approximately 90% of the analyzed particles is also widely employed for this purpose.

(b)



(a)



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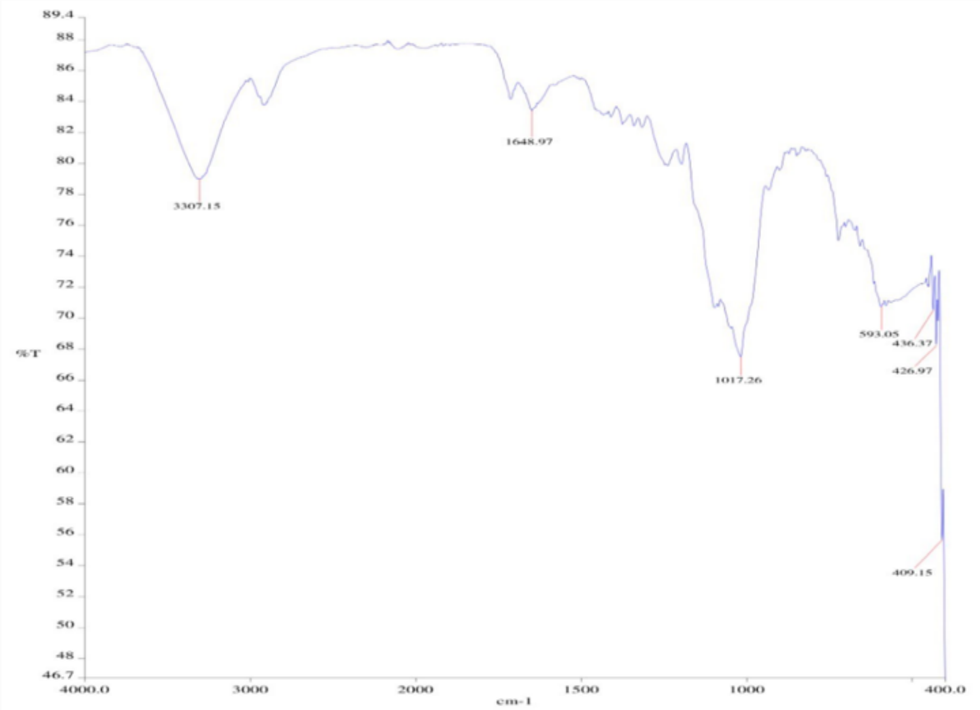

(c)

Figure 5: FT-IR spectra microplastics found in bottled drinking water (a) PP, (b) PE and (c) EVA denotes different types of polymers.

3.4. Dietary Intake of Microplastics

Dietary intake assessments are employed to evaluate beverage consumption patterns among individuals or populations. In this study, we aimed to determine the daily intake of microplastics (MPs) per person to estimate exposure levels and support the development of nutritional guidelines for public health policymaking. The estimated dietary intake of microplastics was calculated based on the mean concentration of MPs detected in bottled water and the daily water consumption rates recommended by the Malaysian Dietary Guidelines 2020 which are 2.0 L/day for adults and 1.7 L/day for children (below 8 years old). Table 2 shows the estimated daily intake for adults and children in Malaysia. Based on the results obtained, the data shows that the amount of microplastics intake is 0.53 particles/kg/day for children and 0.19 particles/kg/day for adults in Malaysia. These figures show that the overall estimation daily intake should not be underestimated. Microplastics can carry harmful chemicals and pollutants that may leach into the human body upon ingestion [25]. Children may be especially vulnerable to critical windows of development, even low-level exposures to MPs. Although the absolute particle counts appear low relative to other dietary sources, the ubiquity and persistence of microplastics mean that cumulative exposure combined with inhalation and ingestion of food could amplify adverse outcomes over a lifetime. Despite growing concern over microplastic (MP) exposure, very few studies have rigorously tested their health effects. Most of the available work has been exploratory or descriptive on cataloguing where MPs go in the body, rather than quantifying dose–response relationships or identifying specific molecular mechanisms of toxicity. Thus, our intake estimates underscore the urgent need for in vitro and in vivo investigations at environmentally relevant doses, longitudinal epidemiology, and the establishment of regulatory limits for microplastic content in food and drinking water. By determining the daily intake, it becomes possible to evaluate the potential health risks linked to prolonged exposure to these substances. Apart from that, the reliable data on microplastic intake can inform the public health to raise awareness and educate the public on potential health risks and the importance of safe water consumption practices. On top of the above, data on microplastic contamination in bottled drinking water can support the development of regulations and standards for government to limit microplastic pollution especially during the processing of water sources.

Table 2. EDI estimation for children and adults based on Malaysian Dietary Guidelines 2020.

Group	Mean microplastics particles in bottled water (particle/L)	Ingestion rate (L/day)	Body weight (kg)	Particle/ kg/day
Children	6.13	1.7	19.50	0.53
Adults	6.13	2.0	61.57	0.19

4. CONCLUSIONS

In this study, the quantification and characterization of microplastics in 17 brands of bottled water around Kota Kinabalu, Sabah Malaysia which included natural mineral water (NMW) and packaged drinking water (PDW) were achieved. All analysed samples are found to have been contaminated with microplastics containing four major distinct sizes. The contamination probably comes from the packaging material of bottled drinking water itself. This is proved by the identification of microplastic particles primarily composed of PP and PE polymers, sourced from materials used in packaging, abrasion of bottle caps, and contamination during the filling process. Further exploration into the risk assessment of microplastics (MPs) is essential for comprehending their implications on human health when found in drinking water. Regulatory bodies and policymakers should rigorously oversee the production and packaging of bottled drinking water due to potential significant health hazards for consumers.

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