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Preliminary results on microplastic release from commercial toothbrushes during simulated brushing

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ABSTRACT

Toothbrushes, an essential component of oral hygiene routines, have emerged as an underrecognized source of microplastic (MP) release, posing potential environmental and health risks. This study aimed to quantify and characterize plastic particles released from commercially available toothbrush brands using microscopy, Fourier transform infrared and μ-Raman spectroscopy. Simulated toothbrushing was performed on a 3D-modeled zirconium dental arch twice daily for seven days under realistic conditions. All toothbrushes released MPs regardless of brand, with the least expensive brand generating the highest number, averaging 39 particles per day. The particles released varied in shape, including fragments, fibers, films, and pellets, and ranged in size from 8 to 1995 μm. Structural characteristics such as bristle shape and material composition (e.g., polybutylene terephthalate and nylon) were found to influence fragmentation and MP generation. These polymers, known for their durability and persistence, raise concerns due to their potential for bioadhesion and bioaccumulation in the oral cavity or receiving environment. The findings also highlight potential oral and systemic health risks, including inflammation triggered by mucosal absorption of small MPs. To mitigate such risks, the results underscore the urgent need to incorporate more sustainable and environmentally friendly materials and design strategies in oral care products from the outset.

1. Introduction

Among the fixtures of modern life, plastics offer numerous advantages; however, their improper disposal at the end of their useful life can lead to adverse consequences for both the environment and human health [2,5]. This concern is particularly critical due to the decomposition of plastic material and waste into micro- and nano-sized polymeric particles [29]. In this context, plastics have also become increasingly prevalent in medical applications, including dentistry [22], where disposable protective equipment and packaging contribute to plastic waste accumulation [4]. Concerns about microplastics (MPs) are escalating due to their widespread presence, resistance to degradation, and cocktail-like behavior [20,27]. These particles can enter the human body through inhalation, ingestion, and skin contact [25], and once inside, they resist clearance by the immune system, potentially leading to chronic local or systemic inflammation [30]. Within the scope of oral health, toothbrushes are widely used in daily hygiene routines. Typically composed of plastic components, toothbrushes can release MPs during use due to breakdown of bristles, triggered by mechanical forces, temperature, and pH in the oral environment [10,11]. Despite increasing awareness, research on MPs from personal dental care products remains limited [21], including acrylic and composite resins [8], orthodontic aligners [10,18], and oral health products such as toothbrushes [11,23] for sustainable dental practices [12]. The presence of MPs in the oral cavity remains difficult to trace, as it is challenging to distinguish between particles released from toothbrushes, toothpaste or saliva debris under real-life conditions. Although some polymeric particles may be removed during rinsing, their bioadhesive properties enable them to adhere to oral tissues, such as tooth surfaces, gingival sulcus and pockets, the tongue and its root, cheek and palate mucosa, the floor of the mouth, and the tonsils, potentially leading to local or systemic effects.

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To contribute to this relatively underexplored topic, the present study aims to investigate the release of MPs from commercially available toothbrushes using μ-Raman spectroscopy to understand particle release mechanisms under realistic experimental conditions. Considering the environmental impact of MPs and their association with cellular inflammatory responses, evaluating their effects on periodontal health and disease could be valuable for clinical diagnosis and treatment maintenance.

2. Materials and methods

2.1. Model zirconium arch and toothbrushes

To evaluate the release of MPs from toothbrushes, monolithic zirconium, a material widely used in dental prosthetic restorations due to its non-plastic and wear-resistant properties, was used (see inset in Fig. 1). An intraoral scan of a periodontally and dentally healthy patient was recorded in 3D using Trios (3Shape, Copenhagen, Denmark). The recorded image was then modeled and milled in 3D from monolithic zirconia using Cerec (inLab MCX5 CAD-CAM, North Carolina, USA). The present study was designed to assess the most frequently purchased models of the most preferred brands of toothbrushes that hold a high market share (i.e., >80 %) in Türkiye. To this end, a total of six different brands of toothbrushes (brands A, B, C, D, E, F) with medium hardness were selected and obtained from the same store. By narrowing the product focus, the study aimed to minimize confounding variables and establish a baseline for future comparative research. This methodological approach aligns with established practices in exploratory environmental health studies, as detailed in Text S1 of the Supplementary Material. Additionally, brushing simulations were performed without toothpaste to eliminate potential interferences from toothpaste-derived particles [28].

2.2. Toothbrushing simulation

The model arch was used for toothbrushing twice daily (morning and evening), for 2 min each time over a period of 7 days, mimicking optimal daily oral hygiene habits [1,14]. To enhance the robustness of the experimental design, brushing was performed by a single experimenter: a healthy 29-year-old female dentist and periodontist with formal training in oral hygiene. During each brushing session, the bristles were rinsed every 30 s using 5 mL of pre-filtered deionized water delivered via a glass syringe (Sanitex, Eternamatik Glass). The resulting 20 mL of pre-filtered rinse water was collected in glass beakers (Borosil Glass Beaker) and covered with aluminum foil until filtration. Each 20 mL sample was filtered using a vacuum filtration system (Millipore) with Whatman glass fiber filters (47 mm, 1.6 μm pore size). The particle-loaded filters were placed in glass petri dishes and dried in an oven at 55 °C (Nüve Fn 500, TR) for subsequent analysis.

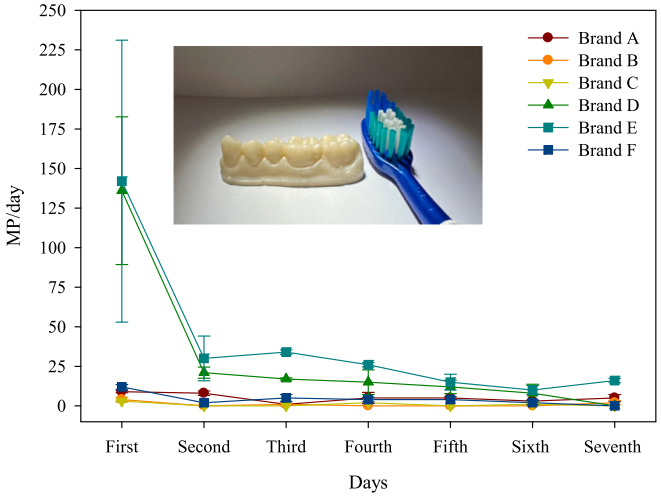


Fig. 1. Number of daily MPs released by all brands ($n = 2$ for each brand). Inset figure shows a model zirconia arch used in toothbrushing activity.

2.3. Visual and spectroscopic analysis

The visual inspection was conducted in two parts, as detailed in Text S2 of the Supplementary Material. First, the morphological properties of the particles released from toothbrushes were investigated using a stereomicroscope (Carl Zeiss, Axiocam 105 color, Germany) at 1.6×, 2×, and 5× magnifications. Second, the condition of toothbrush bristles before and after use was analyzed using optical microscopy (Carl Zeiss, Axioscope 5, Germany) at 10× and 20× magnifications. To identify and characterize the chemical composition of the toothbrush materials, Fourier transform infrared spectroscopy-attenuated total reflectance (FTIR-ATR) was employed using an IR Tracer-100 spectrometer (Shimadzu, Japan) with a scanning range of 4000–400 cm^{-1} and a spectral resolution of 4 cm^{-1}. Additionally, chemical characterization of particles released from toothbrushes was conducted using μ-Raman spectroscopy (Renishaw Plc, Wotton-under-Edge, U.K.). Spectra were acquired with Leica 5× and 20× long-range objectives and a 532 nm laser, optimized with an extended scan range (400–4000 cm^{-1}), laser intensity (0.001–10 mW), exposure time (10 s), and acquisition time (1). Due to the considerable time required for analysis, examining all particles on the filter surface was deemed impractical [3]. Raman spectrometric peaks were interpreted using reference data from the public spectra website (https://publicspectra.com). ImageJ (FIJI) software was used to quantify MP sizes. To ensure the reliability and accuracy of the data, rigorous quality control measures were applied, as detailed in Text S3 of the Supplementary Material.

3. Results and discussion

3.1. Structural characteristics of toothbrushes

To eliminate potential sources of interference and minimize the overestimation of particle counts, the toothbrush brands were analyzed in three separate parts: the packaging box, the handle, and the bristles. Analysis of the packaging boxes revealed that they were primarily composed of polyethylene terephthalate (PET), with additional components including polyester (PES), polyvinyl chloride (PVC), and polypropylene (PP) (Table S1). Examination of the handles showed variation between brands. Brands A and C, whose handles consist of a single part, were produced from PP, while Brand D was produced from liquid paraffin. The remaining toothbrushes (B, E, F) had handles composed of two segments: the first made of PP, and the second of liquid paraffin (Table S2). FTIR analysis of the bristles revealed significant material diversity. The bristles of Brand A consisted of nylon 6,10 across all three colors (white, blue and green). Brands B and F, though differing in bristle color (white and blue), used polybutylene terephthalate (PBT). Brand E also used PBT bristles. Brand C employed only white bristle, made of nylon 6,10. Notably, Brand D featured a mix of bristle materials: three were PBT, one was nylon 6,10, and one was identified as liquid paraffin (Table S3). These findings demonstrate the diversity of materials used in toothbrush production and packaging. The differences in bristle composition (PBT, nylon, or liquid paraffin) affect properties such as stiffness and water absorption, which in turn influence durability during brushing. The detection of liquid paraffin in the bristles may indicate a surface treatment or protective coating. On the other hand, optical microscopic inspection further revealed manufacturing irregularities. Some brands exhibited uneven bristle bundles, poorly cut tips, and in certain cases, rounded tips typically regarded as desirable (Fig. S1). Brand B uniquely presented with pointed bristle tips, which could lead to increased fragmentation under mechanical abrasion, or

cause epithelial injury [9]. In light of these findings, a more comprehensive evaluation of potential MP release based on both material composition and bristle morphology is essential for improving oral healthcare safety and product sustainability.

3.2. Abundance and release characteristics of MPs

Following the completion of brushing simulations, the number of particles released by each toothbrush was determined. A total of 84 filters were initially analyzed under an optical microscope (Fig. S2), revealing 1409 particles across all brands over the 7-day brushing period, with individual counts ranging from 147 to 399. Among these, 559 particles were confirmed as MPs via Raman spectroscopy, with brand-specific counts ranging from 6 to 273. As presented in Table 1, the highest MP release was observed in Brand E (273 ± 46), followed by Brand D (209 ± 47), Brand A (36 ± 3), Brand F (29 ± 4), Brand B (7 ± 2), and Brand C (6 ± 1). Notably, the majority of MP particles were associated with brands E, D, and A whose bristles were composed of PBT and nylon, as shown in Table S3. These results suggest that the material composition of bristles may significantly influence MP release levels during brushing. However, the literature presents conflicting evidence on this matter. Kaneyasu et al. [17] reported no significant increase in abrasion scores for PBT bristles after use when compared to nylon. Conversely, Protyusha et al. [23] have asserted that nylon toothbrushes may release considerable quantities of MPs due to mechanical abrasion that occurs during brushing. These contrasting findings indicate that it remains unclear whether PBT bristles are more resistant to abrasion than nylon bristles. Importantly, not all particles identified were necessarily released from the toothbrushes or polymeric in nature. This was evidenced by discrepancies in the morphology (e.g., color) and structural composition when compared to the toothbrushes and blank samples. Overcounting may have occurred due to three factors: particles that were electrostatically adhered to toothbrushes, carry-over between trials, and airborne particles found in blank samples, which were excluded from final results. In this context, as shown in Fig. 1, the total number of plastic particles released from each toothbrush on a daily basis was examined. Most brands exhibited a high particle release on the first day, followed by a marked decline from the second day onwards and subsequent stabilization at lower levels. The most notable decreases were observed in Brands D and E, with initially released approximately 135–145 particles.

In contrast, other brands showed lower and more stable release patterns (in order of A > F > B > C) from the beginning. The sharp initial release in Brands D and E may reflect variations in bristle quality, manufacturing process tolerances, or material durability. Among these, Brand E was identified as the source of the highest number of MPs, averaging 39 particles released per day (Fig. S3). In particle-based analysis, a varying degree of standard errors (1–47) was observed among the released particles from toothbrushes on a daily basis, indicating more consistent outcomes compared to the broader variability reported (30–120 particles per brush) in the literature [23]. These results demonstrate a notable divergence in MP release patterns during routine toothbrush use, providing compelling insights into the environmental consequences of such practices.

To mitigate the potential for overestimation, it is essential to evaluate MPs release under real-life brushing conditions that accurately simulate daily oral hygiene routines. However, a significant disparity exists in reported MP quantities released from toothbrushes. For instance, Protyusha et al. [23] found that toothbrushes released an average of 67 MPs per brush using simple extraction methods. In another study, Raman imaging revealed approximately 17 particles within a 1.2 mm × 1.2 mm area or an estimated 22,000 particles over a 25 mm × 75 mm glass after simulating brushing by pressing toothbrushes are onto glass surfaces [11]. Jeong et al. [15], using optical microscopy, observed MP release from bristle tips ranging from 3.6 % to 86.2 % across different products. Notably, toothbrushes with thinner bristles were more prone to fragmentation, suggesting the influence of bristle design and material composition on MP generation [15]. Collectively, these findings reinforce that toothbrushes may be a significant source of MPs, with implications for both environmental burden and human exposure to polymeric particles.

3.3. Morphology and chemical characterization of MPs

The toothbrushes were subjected to a second examination under the stereomicroscope, with the objective of evaluating the extent of wear on the bristles. As presented in Table 1, the released MPs exhibited diverse forms, including fragments, fibers, films, and pellets. Film-shaped MPs were predominant in Brand E (84.6 %), followed by Brand D (77.5 %), Brand F (51.7 %), and Brand C (50 %). In contrast, Brand B showed the highest proportion of fragments (66.7 %), while Brand A yielded the most fibers (36.1 %). These morphological differences suggest that bristle composition and structural wear can influence the shape of MPs released. Compared to the literature, Protyusha et al. [23] reported that the most common MP forms released from toothbrushes were fibers (38.2 ± 29.5), fragments (28.0 ± 12.0), and beads (0.8 ± 1.3). Fang et al., [11] also emphasized that brushing technique, force and style applied can cause bristle bending and twisting, increasing particle release. The diversity of MP-shapes highlights the environmental implications of toothbrush use and highlights the need for alternative materials in oral hygiene products (Fig. S4).

MP particles ranging in size from around 2 mm to 8 μm were identified through optical analysis. Brand C had the largest average particle size (277 ± 404 μm), followed by Brand A (256 ± 412 μm), Brand F (171 ± 160 μm), Brand E (131 ± 90 μm), Brand D (106 ± 233 μm) and Brand B (97 ± 94 μm) (Table 1). There were notable differences in average size by morphology between the brands (Fig. S5). For instance, fiber-shaped MPs reached up to 1094 μm in Brand C, while smaller values were found in Brand B (e.g., 277 μm). Fragment type MPs were generally smaller, with Brand F having the largest average (254 μm). Pellet types had the smallest averages (e.g., Brand A: 19 μm), while films showed a broader size range (e.g., Brand F: 195 μm). For comparison, Protyusha et al., [23] reported mean MP sizes of 36.4 ± 18.8 μm, 29.0 ± 15.5 μm, and 1.6 ± 1.8 μm for the size typology of <0.1 mm, 0.1–0.3 mm, and > 0.3 mm, respectively, obtained from five brands of toothbrushes. Overall, the data indicate that MP release is especially pronounced during the initial use phase, likely due to bristle bundle irregularities or tip-cutting defects. These factors, combined with individual brushing habits and

Table 1
Morphological characteristics of MPs released from toothbrushes.

Brand	ΣMPs (Mean ± SD)	Shape (%)				Size (μm)			Color					
		Fiber	Fragment	Pellet	Film	Min.	Max.	Mean ± SD	Blue	Dark blue	Yellow	White	Pink	Purple
A	36 ± 3	36.1	30.6	5.6	27.8	8	1995	256 ± 412	36					
B	7 ± 2	16.7	66.7		16.7	20	277	97 ± 94						6
C	6 ± 1	16.7	33.3		50	42	1094	277 ± 404				6		
D	209 ± 47	5.3	9.1	8.1	77.5	13	1924	106 ± 233	198	11				
E	273 ± 46	1.8	1.8	11.7	84.6	15	531	131 ± 90	161		112			
F	29 ± 4	0	24.1	24.1	51.7	16	692	171 ± 160					29	

applied force, have the potential to accelerate bristle deformation and particle detachment.

To verify that the MPs found on the filters originated from the toothbrushes, μ-Raman spectroscopy was employed (Fig. 2 and Fig. S6). Unlike FTIR, which is sensitive to water signals, Raman spectroscopy produces relatively weak water interference, making it more suitable for analyzing moist or water-exposed samples, such as used toothbrushes. Subsequently, the peak values obtained from FTIR, which served as a reference for the polymer types typically found in toothbrush bristles, were compared with those derived from the Raman analysis. As can be seen fromFig. 2, the results confirmed that the released particles matched the polymers used in bristle materials.

The majority of fiber-shaped MPs were found to originate from toothbrushes made of nylon. Nylon is preferred in bristle production due to its stiffness, which enhances plaque removal efficiency [16]. However, its high-water absorption property leads to a gradual loss of stiffness in humid environments, reducing its long-term durability [13]. In contrast, most fragment-shaped MPs originated from toothbrushes with PBT bristles. PBT is a thermoplastic polyester known for its low water absorption, heat resistance, and chemical stability, making it more suitable for prolonged use in wet applications [16]. Even so, Kaneyasu et al. [16] observed a significant reduction in bristle stiffness for both soft and medium stiffness PBT bristles after two months of use. While nylon bristles are initially stiffer than PBT, they degrade faster due to water uptake, potentially making them less durable in the long term. In terms of sustainability, Mazur et al. [20] reported that silicone bristles exhibited 14 % lower environmental impact compared to nylon. Overall, adopting toothbrush models with replaceable heads could plastic waste and limit the release of polymeric particles over time.

3.4. Implications for oral health

The release of MPs from toothbrushes has given rise to concerns regarding potential health risks, including local or systemic inflammation due to the accumulation of particles in the oral cavity [6]. To assess such risks, a polymer hazard index (PHI) was calculated for the polymers identified in toothbrushes. This index offers insight into the potential hazards associated with each polymer [4,23]. In accordance with the prescribed methodology [19,26], brands A (47) and C (47), both containing nylon 6,10, exhibited the highest hazard scores (PHI: 4700), placing them in the extreme hazard category (level V). This is particularly noteworthy given that these brands released fewer MPs on average than others (in order of E > D > A > F > B > C), indicating that hazard potential is not solely dependent on particle quantity but also on polymer composition.

While PHI offers valuable insight into the potential chemical hazards of polymers, understanding the biological fate of these particles in the human body is essential for a comprehensive risk assessment. The human body is primarily exposed to MPs through ingestion, as is the case in the field of dental science. Although the majority of MPs are removed by spitting after use, there is a possibility that some may adhere to dental hard tissues or oral soft tissues and then enter the digestive system [23]. Notably, the retention and uptake of MPs are strongly influenced by their size. While larger particles (> 20 μm) are likely to be excreted via the gastrointestinal tract, particles between 5 μm and 20 μm may be absorbed by intestinal epithelium through endocytosis or paracellular diffusion [24]. In the present study, the MPs ranged from 8 μm to 1995 μm, suggesting that while many are likely to be excreted, smaller particles could be absorbed and potentially trigger inflammatory responses.

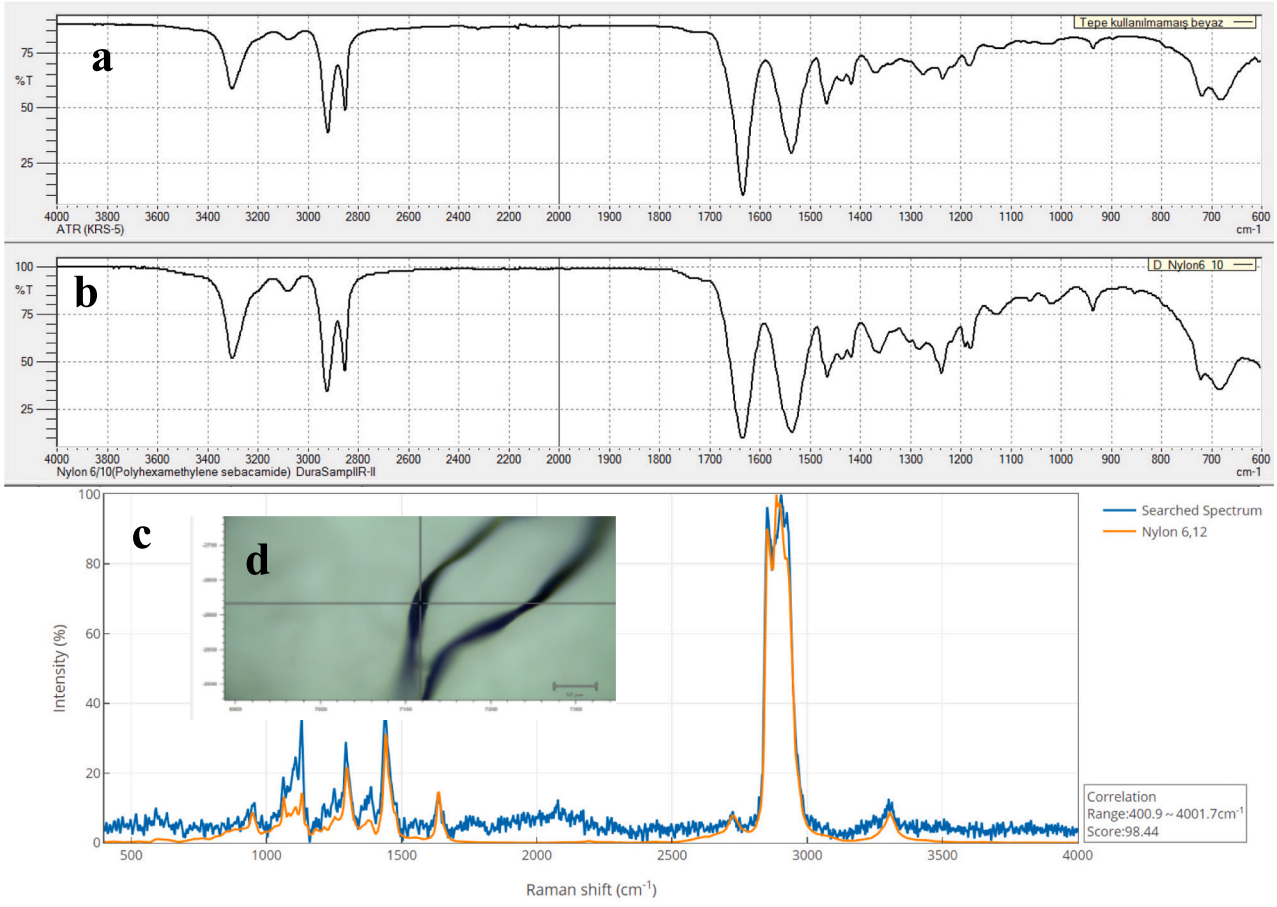


Fig. 2. A representative plot for the spectroscopic analysis of polymer particles that had become detached from the toothbrush bristles of brand C. a. FTIR spectrum, b. FTIR spectrum of nylon polymer, c. Raman spectrum of the particle on the filter, d. Raman image of the particle on the filter.

Experimental studies also support this concern. Caputi et al. [7] reported that MPs isolated from marine environments altered cell morphology and induced inflammatory signaling (NFkB/MyD88/NLRP3 pathway) in human gingival fibroblasts (hGFs). Specifically, exposure to MPs at varying sea depths (i.e., 1 and 78 m) increased the expression of inflammatory markers and reduced cellular metabolic activity. These findings suggest that oral exposure to MPs, especially smaller particles, may not only impact local tissues but also contribute to systemic inflammation. Taken together, both the chemical composition and morphological characteristics of MPs, regular exposure to plastic particles at (microplastics) or below the micron limit (nanoplastics) may contribute to cumulative health risks. Given the potential for cellular uptake and inflammation, particularly in gingival tissues, further research is warranted to explore the link between MP exposure and periodontal disease progression.

4. Conclusion

This study demonstrates that toothbrushes contribute to the release of tiny plastic particles into the environment during routine oral hygiene. Daily brushing leads to the emission of microplastics (MPs), primarily from bristles, in various forms (i.e., fragments, fibers, films, and pellets). These findings highlight not only the variability in MP morphology and materials (e.g., PBT and nylon), but also the chronic nature of exposure through repeated daily use. In light of these observations, it is important to critically examine the limitations of this study is essential to better understand the broader implications for environmental and human health. To enhance the robustness and generalizability of future research, factors such as larger sample sizes, real-use scenarios involving human participants, and variations in brushing techniques should be considered. Moreover, variables such as using multiple toothbrushes from different production batches, including electronic models, and accounting for the role of toothpaste and saliva on MP release are essential. Realistic usage patterns, particularly differences related to gender, age, and brushing behavior should also be included in future investigations.

CRediT authorship contribution statement

Çağla Öztürk Aytulun: Writing – original draft, Visualization, Methodology, Investigation. **Parisa Akbari Dana:** Writing – original draft, Visualization, Methodology. **Zhala Gachayzade:** Methodology. **Kadir Gedik:** Writing – review & editing, Methodology, Conceptualization. **Nur Balci:** Project administration, Methodology. **Hilal Toygar:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.microc.2025.114680.

Data availability

Data will be made available on request.

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