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Review

The unseen perils of oral-care products generated micro/nanoplastics on human health

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ABSTRACT

The extensive use of plastics in modern dentistry, including oral care products and dental materials, has raised significant concerns due to the increasing evidence of potential harm to human health and the environment caused by the unintentional release of microplastics (MPs) and nanoplastics (NPs). Particles from sources like toothpaste, toothbrushes, orthodontic implants, and denture materials are generated through mechanical friction, pH changes, and thermal fluctuations. These processes cause surface stress, weaken material integrity, and induce wear, posing health risks such as exposure to harmful monomers and additives, while contributing to environmental contamination. MPs/NPs released during dental procedures can be ingested, leading to immune suppression, tissue fibrosis, and systemic toxicities. The gut epithelium absorbs some particles, while others are excreted, entering ecosystems, accumulating through the food chain, and causing ecological damage. Although analytical techniques have advanced in detecting MPs/NPs in oral care products, more robust methods are needed to understand their release mechanisms. This review explores the prevalence of MPs/NPs in dentistry, the mechanisms by which MPs/NPs are released into the oral environment, and their implications for human and ecological health. It underscores the urgency of public awareness and sustainable dental practices to mitigate these risks and promote environmental well-being.

1. Introduction

Oral health is considered essential to daily hygiene, yet concerns are raised about microplastics (MPs) and nanoplastics (NPs) released from plastic-based dental materials like fillings, sealants, and implants, potentially impacting health and the environment. Dental practices have evolved significantly over time, transitioning from the use of ivory, bone, and gold in dental prostheses and braces to the more modern use of resin-based composites (RBCs). These RBCs, such as Poly(methyl methacrylate) (PMMA), Bisphenol A-Glycidyl Methacrylate (Bis-GMA),

Abbreviations: NPs, Nanoplastics; MPs, Microplastics; RBC, Resin-Based Composite; MMA, Methyl methacrylate; PMMA, Poly methyl methacrylate; Bis-GMA, Bisphenol A-Glycidyl Methacrylate; UDMA, Urethane dimethacrylate; TEGDMA, Triethylene glycol dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; PET, Polyethylene terephthalate; BPA, Bisphenol A; MMP, Matrix metalloproteinase; CAD/CAM, Computer-aided design/computer-aided manufacturing; NAC, N-Acetyl cysteine; RM-GIC, Resin-modified glass-ionomer cement; POPs, Persistent organic pollutants; PCB, Polychlorinated biphenyl; USEPA, United States Environmental Pollution Agency.

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Urethane Dimethacrylate (UDMA), and others, now replace amalgam in dental procedures (Bowen, 1956; Van Landuyt et al., 2007). Modern dental tools, such as toothpaste, toothbrushes, floss, and aligners, also rely heavily on high-grade plastics. While plastics serve vital functions in modern dentistry, their unintentional release as microplastics (MPs) and nanoplastics (NPs) during routine dental procedures and oral care is emerging as a significant environmental and health concern.

Plastics are synthetic materials made of long-chain polymers, featuring a main organic chain, side-linked molecular groups, and additional organic groups. The production of plastics is also accompanied by the generation of minuscule plastic particles, known as microplastics (MPs) (<5 mm) and nanoplastics (NPs) (<100 nm). MPs/NPs are released as directly manufactured particles or from the disintegration of larger plastic debris via mechanical forces, exposure to ultraviolet radiation, and biological processes (Saha et al., 2024). These particles can be toxic to the tissues and organs of the human body, including the gastrointestinal tract, and oral biome (Haldar et al., 2023; Prata et al., 2020; Saha et al., 2024). The various kinds of MPs/NPs found in oral-health care materials like toothpaste, toothbrushes, dental aligners, and RBCs have been confirmed by researchers with the aid of high-end techniques like SEM, FTIR, IR, and Raman spectroscopy (Gniadek and Dąbrowska, 2019; Jung et al., 2023; Markic et al., 2023; Moura et al., 2023; "The release of polylactic acid nanoplastics (PLA-NPLs) from commercial teabags. Obtention, characterization, and hazard effects of true-to-life PLA-NPLs," n.d.). The identified MPs/NPs have been tested for their toxic effects when installed in the oral environment, owing to their varying microbial environment, pH, and temperature fluctuations. The release of these particles in the human body due to activities like chewing results in varying underlying problems like tissue inflammation, abnormality in the gut microbiome, and disrupted endocrine and DNA damage (Szczepanska et al., 2012; Hirt and Body-Malapel, 2020; Wu and Seebacher, 2020; Prata et al., 2020; Saha et al., 2024).

MPs can also enter the human digestive and respiratory tract through aerosols generated during dental procedures (Choudhury et al., 2023). They show hydrophobic properties which allow them to adsorb toxic chemicals including organic pollutants. MPs/NPs from RBCs are liberated into wastewater post-polishing & finishing processes during their clinical applications. The extensive usage of RBCs leads to the production of a substantial amount of fine micro-particulate waste adding to the microplastic pollution in the environment (Chandran et al., 2021). Other forms of MPs like microbeads are synthetically manufactured and added as exfoliants in some toothpastes. These washout products act as contaminants entering the drainage system through household waste. Consequently, these plastics are clogging up oceans because of the non-filtration capability of wastewater treatment plants. These plastics do not decompose and are absorbed or consumed by aquatic animals. The sewers convey these pollutants into lakes or oceans, which can also get transferred to the human system through the consumption of seafood or fruits and vegetables that have absorbed plastic-contaminated water (Domenech and Marcos, 2021). Traces of MPs/NPs have also been detected in urine and blood which are either directly excreted out or indirectly discarded in the hospital or municipal wastes ultimately entering the environment (Çobanoğlu et al., 2021).

2. Presence of micro/nanoplastic in dental products

2.1. Daily oral care products

MPs and NPs are present in a wide range of cosmetics and personal care formulations including those used for oral hygiene practices (Duis and Coors, 2016; Hernandez et al., 2017; Praveena et al., 2018). Traditional toothbrushes, for instance, have bristles composed of nylon or a thermoplastic elastomer based on their properties of inhibiting microbial growth (Ballini et al., 2021; de Carvalho et al., 2019; Merl Josef, 2007). A recent study assessed microplastic contamination in common oral care products across India, finding all products tested were contaminated with MPs. Toothbrushes had the highest levels (30–120 particles/brush) and mouth freshener sprays had the lowest (0.2 – 3.5 particles/ml). The primary MPs identified included fragments, mostly colorless, and consisted mainly of polyethylene (52 %). Risk assessments showed high potential exposure, especially through daily mouthwash use (74 billion particles/day) and annual toothbrush use (48,910 particles/person), indicating significant MP presence in these products (Protyusha et al., 2024).

Microbeads are solid particles less than 1 mm, composed of polyethylene, polystyrene, or polypropylene, and are hydrophilic (Limjuco et al., 2020). Because of the grain-like consistency, microbeads are particularly convenient for manufacturers to employ in scrapes or exfoliates. Some toothpaste formulations also contain these hydrophilic polymers as an addon for binding and thickening agents. The microbeads are responsible for governing the release of ingredients to the oral cavity and work as retention agents (Boddupalli et al., 2010). Numerous studies have also confirmed the presence of MPs/NPs in toothpaste products (Allé et al., 2021; Madhumitha et al., 2022; Ustabasi and Baysal, 2020). Polyethylene has been found in four different types of toothpaste marketed in Istanbul (Ustabasi and Baysal, 2020). A recent study successfully recovered microplastic from 10 different commercially available toothpaste. The main polymers found in these toothpastes were cellophane, polyamide, polyvinyl chloride, and polypropylene. Approximately half of the particles in 50 % of toothpaste samples analyzed were identified as MPs, with a size range between 3.5 μm and 400 μm (Madhumitha et al., 2022).

Another oral care product prevalent in the market and used routinely by a huge population is dental floss. During the flossing process, the frictional action between the floss and tooth surfaces may lead to the release of minute plastic particles into the oral microbiome, raising concerns regarding human safety. An analysis of regular microplastic discharge in India revealed mouthwash to be the major source, contributing an estimated 74 billion particles daily. This was followed by toothpaste (33.4 billion particles/day), tooth powder (22 billion particles/day), and mouth freshener spray (0.36 billion particles/day) highlighting a potential disparity in emission rates across various oral care products (Protyusha et al., 2024). However, the evaluation of annual MPs exposure indicated toothbrushes pose a greater risk, with an average individual getting exposed to 48,910 particles annually (Protyusha et al., 2024). An individual is exposed to different levels of MPs through the regular use of oral care products but, not all of them are ingested. The discarded products are carried out by wastewater systems and sent to waterbodies. Although most of them are expelled or spat out after use there is a possibility that the particles remaining in the oral cavity could be ingested. This necessitates investigations assessing the lifecycle of products like toothbrushes to understand their degradation stages and microplastic release. Additionally, studying microbead interaction with oral tissues can elucidate their adhesion mechanisms. There should be stringent regulatory frameworks to govern the inclusion of MPs in oral hygiene products.

2.2. Orthodontic implants

Orthodontic implants are prosthetic devices that aid in replacing missing teeth and restore functionality in the oral cavity. They can also correct abnormalities or defects in the maxillofacial region. Classified as dentures, crowns, or bridges, these implants are typically constructed from polymeric materials or RBCs. Additional components such as reinforcing fillers, initiators, and pigments, are often incorporated to enhance the implant's properties and appearance. However, these materials are susceptible to degradation caused by mechanical factors such as pH variations, saliva, bacteria, temperature changes, mastication, and abrasion. RBCs like PMMA are used to manufacture the pink acrylic foundation of dentures, which supports the denture teeth and fits over the patient's gums (Jagger et al., 1999). Polymeric materials like polyethylene terephthalate (PET) show promise for manufacturing dental prosthetic components, including retention capsules for implant-retained overdentures (Galo Silva et al., 2019; Valente et al., 2022). PET, and other polymers like polyurethanes, polypropylene, and polycarbonate are used in producing transparent aligners (Daniele et al., 2020; Ho et al., 2021). A recent study demonstrated that clear aligners can be a source of secondary microplastic release (Quinzi et al., 2023). Through simulated oral conditions, researchers identified a correlation between mechanical friction and the release of MPs from aligners. This involved exposing the aligners to artificial saliva for seven days (Quinzi et al., 2023). Orthodontic treatment also involves elastomeric ligatures or rubber bands to correct misaligned teeth mostly in teenagers. A study indicates that these bands can release millions of MPs and NPs into the oral cavity (Fang et al., 2023a). This is particularly concerning for adolescents due to their developmental stage. Orthodontic adhesives are also essential in modern dentistry for attaching dental restorations and prosthetics to the teeth. They are typically composed of a resin base, such as Bis-GMA or UDMA, reinforced with inorganic fillers to improve durability (Craig et al., 2006; Van Landuyt et al., 2007). A study identified MPs present in different dental adhesive samples using SEM and FTIR, in the form of fibers and fragments (Divakar et al., 2024). While the potential release of MPs and NPs from orthodontic implants is evident, there is a critical research gap regarding the precise characterization and quantification of these particles.

2.3. Denture-based acrylic resin

MPs/NPs are typically identified by their increased polymer content, unusual characteristics including insolubility in water, and size requirements. When determining the type of MP/NP, the degradability of the polymer material must be considered. The chemistry of such polymers involves methacrylate-based materials such as PMMA, Bis-GMA, UDMA, TEGDMA, and HEMA, which are used to make the resin matrix of denture materials (Bowen, 1956; Van Landuyt et al., 2007). RBCs used in dentistry comprise 60–80 % filler particles made of inorganic glass joined to and encased in a matrix of organic resin. The matrix makes up most of the composite, while the fibres add strength and rigidity. Resins offer great bonding qualities, whereas composites have high strength, toughness, and wear resistance, making them suitable for dental implants.

Directly placed RBCs often fail to fully polymerize, with monomer conversion rates typically between 60 % and 75 %. This is particularly pronounced at the restoration's base, where conversion rates can be as low as 30 % (Calheiros et al., 2014; Eshmawi et al., 2018; Ferracane and Condon, 1990; Yu et al., 2017). The mechanical properties and durability of RBCs are correlated with monomer conversion rates, with lower conversion levels associated with greater leaching of residual monomers (Olea et al., 1996). This insufficient polymerization in these RBCs may result in the release of residual monomers (Moharamzadeh et al., 2007; Ruse and Sadoun, 2014). Secondary MPs are generated from RBCs as they degrade in the oral cavity or are released during the restoration finishing or polishing (Mulligan et al., 2021). The ester linkages within commonly employed dental resin monomers like BisGMA, TEGDMA, and UDMA are prone to hydrolytic degradation by salivary esterases and cariogenic bacteria, thereby speeding up their biodegradation (Stewart and Finer, 2019).

2.4. Poly (methyl methacrylate)

MMA (methyl methacrylate), frequently utilized as a monomer in denture-based polymers, transforms itself during polymerization into a linear polymer structure called PMMA with additional tertiary amine activators or a temperature-sensitive chemical (benzoyl peroxide) (Vallittu et al., 2017).

PMMA is one of the polymers that are often used to create dental retainers and dentures in dental clinics to reline dentures and temporary crowns and in industries for the fabrication of artificial teeth (Deb, 1998; Nejatian et al., 2019). It is commercially available in a liquid-powder formulation, which constitutes of the polymer PMMA accompanied with additives for enhanced biocompatibility like pigment or acrylic synthetic fibres to mimic the oral tissue environment. It has shown excellent water absorption capability at body temperature for several weeks following installation, which makes it ideal to be incorporated into an oral environment (Kuehn et al., 2005). PMMA is also used to create durable RBCs due to its affordability, good wear resistance, aesthetic qualities, considerable polish, stable color compatibility, good marginal fit, and biocompatibility with oral tissues (D. et al., 2012). PMMA MPs/NPs are found across multiple environmental compartments due to their widespread application of PMMA products and their release during production, usage, and disposal (Mahadevan and Valiyaveettil, 2021). PMMA MPs have been detected in the human liver, heart, and bloodstream, indicating widespread exposure to these contaminants (Boran et al., 2024; Horvatits et al., 2022; Leslie et al., 2022; Yang et al., 2023). As the use of PMMA in dental applications has grown, concerns have emerged about the potential release of MPs/NPs during the various stages of its use.

2.5. Bisphenol A-glycidyl methacrylate

The byproduct of the reaction between glycidyl ester methacrylate and bisphenol A results in Bis-GMA, and its molecular backbone includes pendant hydroxyl groups. Bis-GMA displays less toxicity, shrinkage, and volatility than previously employed RBCs yet retains a high modulus. Bis-GMA was similar to epoxy resin but had methacrylate groups instead of epoxy groups, which enabled rapid polymerization under oral conditions while significantly lowering polymerization shrinkage by about one-third of when preceding materials were used (Bowen, 1982).

Composite resins based on Bis-GMA are now commonly utilized in modern dentistry for a range of dental restorations such as fillings, crowns, and veneers. While Bis-GMA monomers are generally considered safe for dental use, there is a small concern about the presence of unreacted epoxy resin monomers in the finished product. These unreacted monomers can produce allergic responses in certain people, particularly those who are allergic to epoxy resins (Björkner et al., 2011; Niinimaki et al., 1983). Subtractive CAD/CAM manufacturing of RBCs produces substantial microparticulate powder. These CAD/CAM blocks can still release Bis-GMA monomers despite their higher polymerization. The elution of Bis-GMA microparticles can be enhanced by photolytic and oxidative degradation of the resin matrix (Mulligan et al., 2021). Bis-GMA resists hydrolysis by salivary esterases but, exposure to oxygen during sealant placement inhibits complete polymerization at the material's surface. This leads to the release of unpolymerized monomers into the saliva, with the most pronounced leaching occurring shortly after application, gradually subsiding over time (Kingman et al., 2012). While larger than conventional MPs, Bis-GMA monomers have the potential to degrade further within the oral cavity, thereby contributing to the overall microplastic burden.

2.6. Urethane dimethacrylate/ Triethylene glycol dimethacrylate

Certain *in vitro* studies have discovered evidence of residual monomer releases, such as UDMA, HEMA, and comonomer TEGDMA from resin nano ceramic and hybrid ceramics over all periods. The monomer UDMA, is one of the widely used polymers in dental resin, mostly in combination with the polymer Bis-GMA. These formulations also contain other monomers with lower molar masses, such as TEGDMA and diethylene glycol dimethacrylate (DEGDMA), which serve as diluents and reduce the otherwise unmanageably high application viscosity (Rey et al., 2008). On the other hand, HEMA is a low molecular weight monomer, that bears a significant role in most adhesive systems due to its hydrophilic characteristics. This is a monomer that is often found in dental and medical products such as denture base resins and dental adhesives.

In a recent study done on the 50:50 % by weight UDMA: TEGDMA ratio, it was identified that they exhibit a homogeneous smooth surface, an elevated rate of conversion, and strong mechanical strength, which are encouraging for their use in dental resin (Sianturi and Humaidi, 2023). Another research put a spotlight on the cross-linked structural network of Bis-GMA/TEGDMA dental resins and investigated their physicomechanical attributes. The cross-linked network formation was confirmed by observing the molecular weight fraction profiles and radial distribution function (RDF) during polymerization, which also correlated with characteristics like density, glass transition temperature, elastic modulus, and volume shrinkage of the dental resin (Tan et al., 2023).

3. Detection of micro/nanoplastic from dental products

The behavior of MPs/NPs depends on their physical, chemical, and biological characteristics, which are related to the surface, transport, fate, and adsorption depending on their external morphology (Song et al., 2019). Therefore, understanding the surface characteristics of these plastics plays a crucial role in their identification and characterization. Several methods are employed to describe MPs/NPs including Scanning electron microscope (SEM) (Dąbrowska et al., 2021; Jin et al., 2023; Mulligan et al., 2021), mass Spectrometry, thermal gravimetric analysis (Yu et al., 2019), gas chromatography, and optical microscopy. Raman spectroscopy has become more common in the characterization of MPs and NPs due to its higher spatial resolution (Araujo et al., 2018; Ghosal et al., 2018; Luo et al., 2023). Micro-FTIR Spectroscopy is used for the characterization of smaller fractions of MPs (Corami et al., 2020). Scanning Electron Microscope (SEM), Laser diffraction particle size analysis (PSA), micro-Fourier Transform Infrared (FTIR) Spectroscopy, and Potentiometric titration were the techniques used for the characterization of RBCs in wastewater samples (Mulligan et al., 2021). Although several studies have successfully chalked out ways to characterize MPs/ NPs in general, very handful of characterisation techniques have been successfully able to characterize MPs/ NPs specific to dental applications. Some of the high-end techniques used to detect MPs/NPs found in dentistry to date like dental-based resins (RBCs), toothpaste, toothbrushes, and tooth aligners are highlighted in this section.

3.1. Fourier transform infrared spectroscopy

FTIR spectroscopy is a powerful analytical technique used to identify and characterize chemical compounds based on their absorption or transmission of infrared radiation. The sample absorbs certain frequencies of infrared radiation, and the resulting spectrum shows the characteristic absorption peaks or bands that are associated with the different functional groups present in the sample. The intensity and position of the peaks can provide information about the concentration, structure, and bonding of the sample. To characterize, identify, and quantify microplastics in wastewater samples, FTIR spectroscopy is the method that is most frequently utilized (Tagg et al., 2015). This technique can be used on materials with dental origins to characterize microparticles that are released from them into the environment during routine dental procedures since the functional groups are pre-determined. In a study targeted to determine MPs in toothpaste (Madhumitha et al., 2022), FTIR analysis showed the presence of polyethylene microparticles through characteristic signals accompanied by microscopy images which revealed opaque, irregular particles of sizes similar to MPs found in toothpaste, compared to another study (Praveena et al., 2018). The microscopic image of the microplastic particles identified has been shown in Fig. 1a. According to Mulligan and his team, microparticles being released from RBCs showed an alteration on their surface after analyzing with micro-FTIR, indicating plausible biofilm formation or monomer release on environmental exposure (Mulligan et al., 2021). As shown in Fig. 1b-i, the optical images of the microparticles tested were analysed for the location of targeted molecules under the absorption spectra of 4000 and 750 cm^{-1} using false-color imaging shown in Fig. 1b-ii. Fig. 1b-iii shows the micro-FTIR of the portion of the area bearing microparticles (Mulligan et al., 2021). Another study found polyethylene using both microscopy images and FTIR in four varieties of toothpaste like toothpaste for protection against teeth sensitivity (Fig. 1c-i), whitening with calcium and fluoride toothpaste (Fig. 1c-ii), whitening toothpaste (Fig. 1c-iii) and bio-active whitening toothpaste (Fig. 1c-iv). The ATR-FTIR spectra of freshly new CAD/CAM (control), glass (from reference library), epoxy resin (from reference library), and butyl methacrylate or isobutyl methacrylate have been shown in Fig. 1e. (Ustabasi and Baysal, 2019). However, certain limitations exist when characterizing MPs using FTIR due to their chemical changes under various factors. A recent study on marine microplastic particles using FTIR found that oxidative degradation hindered the identification of polymers due to changes in the spectra and a lack of adequate reference spectra for the degradation products of the polymers (Magnusson and Norén, 2014).

3.2. Scanning electron microscope (SEM)

SEM is commonly used to study the morphology, topography, and composition of various materials due to its excellent depth of focus and thus provides images with high resolution. To create a digital image of the surface of the sample, an appropriate detector is used which collects the various signals generated due to the interaction of a focused electron beam with atoms of the sample. In a study, RBC components in both directly placed polymerized form to mimic daily clinical use and CAD/CAM ingots previously polymerized and produced by CAD/CAM technology were used to analyze the presence of MPs in them. The data from particle size analysis (PSA) concluded the presence of particles in a microparticulate range that is less than 5 mm, indicating the size of a microplastic. Some particles showing a higher surface area were discussed to have been accumulated accompanied by an increase in elution of a monomer into aquatic environments, indicating the presence of materials having Bis-GMA, since its presence was found in other similar studies with samples in water. This was supported by the SEM pictures (Fig. 1d-i,ii,iii) at 100 μm, 10 μm, and 5 μm scale range respectively, which also demonstrated an abundance of submicron particles in addition to the RBC particle aggregation (Mulligan et al., 2021). A novel study on the recent emerging artificial tooth aligners showed the first-time release of secondary microplastics from these aligners by examining them by SEM. The MPs from seven different brands of such tooth aligners were found to be in the range of 5–20 μm (Quinzi et al., 2023).

3.3. Infrared and Raman spectroscopy

Raman spectroscopy measures the relative frequencies at which a material scatters light, whereas infrared (IR) spectroscopy measures the absolute frequencies at the point a sample absorbs the emitted radiation. Both methods examine how radiation interacts with molecular vibrations, but they differ in how photon energy is transmitted to the molecule via altering its vibrational state. In a study, the amount of MPs and NPs contained in toothbrush samples was characterized using these two techniques. A study on orthodontic aligners confirmed MPs release with the aid of Raman Microspectroscopy to evaluate the chemical composition of their polymeric matrix revealed the presence of PET (polyethylene terephthalate) in 5 brands of aligners and polyurethane in two of such brands (Quinzi et al., 2023). Smaller microplastics (<100 μm) from the oral environment pose challenges for detection using Raman spectroscopy, highlighting that relying solely on visual identification is inadequate for studies involving small microplastics. (Lenz et al., 2015). The studies conducted to determine various techniques used to characterize MPs/NPs from dental materials like toothpastes, aligners, and RBCs have been listed in Table1.

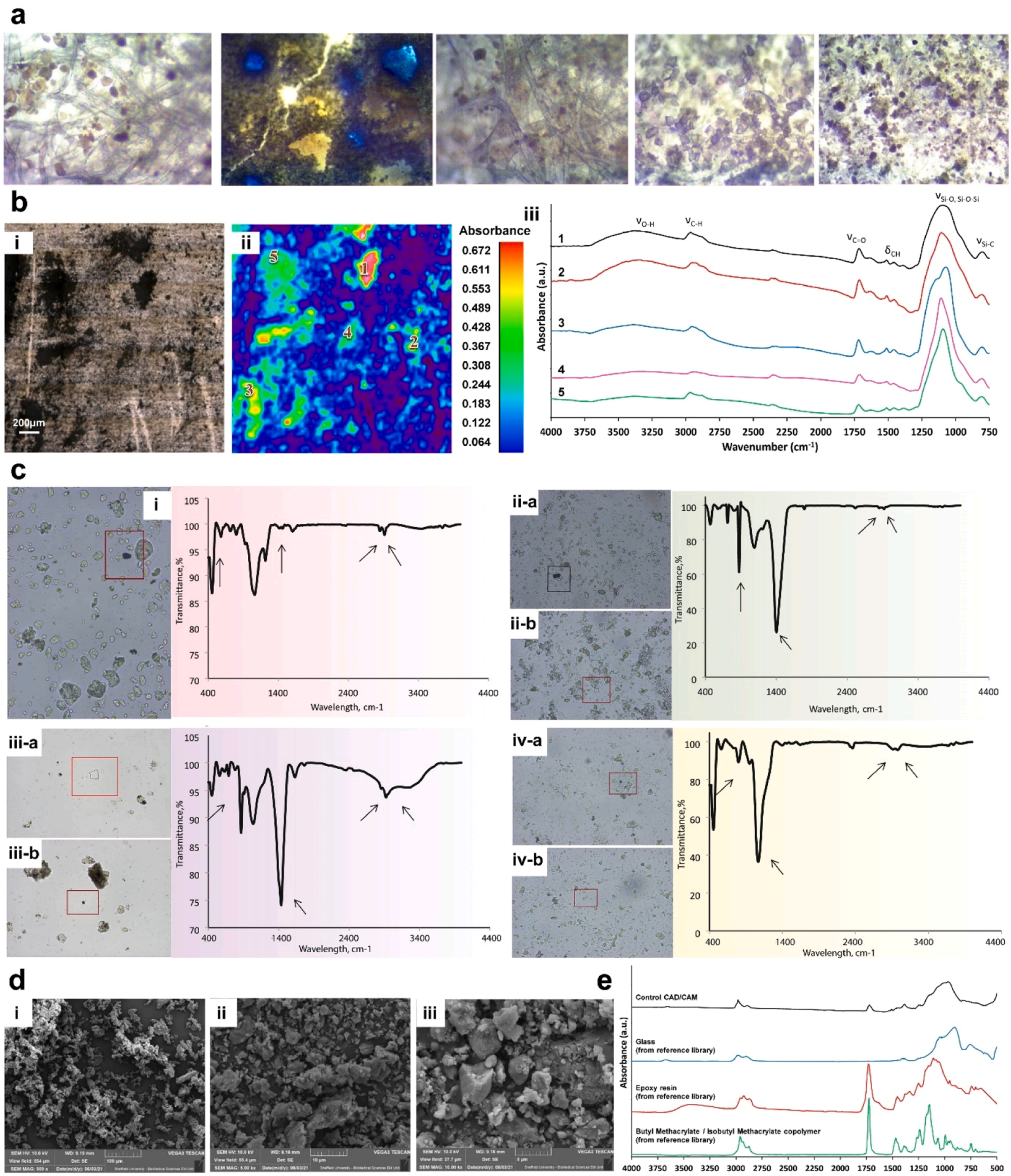

Fig. 1. Characterization of MPs in dental-based products. (a) SEM images of microplastic from toothpaste (Praveena et al., 2018). (b) Reflectance micro-FTIR spectroscopy commercially available direct replacement microparticles, i) Optical image of commercially available direct replacement microparticles on stainless steel surface, ii) Molecules with absorption bands between 4000 and 750 cm− are shown in the false-color image, iii) At varied locations on the false-color picture, reflectance micro-FTIR spectra of the region containing commercially available direct replacement microparticles. (c) Microscopic and FTIR images of MPs from various toothpaste samples. i, ii-a, iii-a, and iv-a are the microscopic images of opaque microplastic particles. ii-b, iii-b, iv-b are the microscopic images of transparent microscopic particles. Right after each microscopic image represents the FTIR result, and the presence of polyethylene is indicated by arrows. (d) SEM images of commercially available direct replacement microparticles. (e) ATR-FTIR spectra. Fig.
(a) Images adapted from (Praveena et al., 2018). (b) Images adapted and modified from (Ustabasi and Baysal, 2019). (c) D & e adapted and modified from (Mulligan et al., 2021).

Table1
Characterization techniques used to determine the presence of MPs in several dental-based products.

Dental products	Characterisation techniques	Method	Ref.
Toothpastes	FTIR	The filtrates from toothpastes solution were dried. This mixed with water resulted in the MPs to float, which were analysed by FTIR after drying.	(Ustabasi and Baysal, 2019)
	SEM	The tooth aligners were submerged in an artificial salivary solution and stirred for 5 hours/ day for a week. The saliva was filtered out and then the filtrates were analyzed.	(Quinzi et al., 2023)
Tooth aligners	Raman Spectroscopy	The tooth aligners were submerged in an artificial salivary solution and stirred for 5 hours/ day for a week. The saliva was filtered out and then the filtrates were analyzed.	(Quinzi et al., 2023)
	SEM	Commercial and RBCs treated using CAD/ CAM technology were analyzed by SEM images showing MPs along with RBC aggregates.	(Mulligan et al., 2021)
Resin-based composites (RBCs)	FTIR	Epoxy resin-based composites made by polymer filling with pure and functionalized multiwalled carbon nanotube (MWCNT) composites and released microplastics analyzed using FTIR.	(Sahle-Demessie et al., 2018)

4. Mechanisms responsible for the release of micro/nanoplastic

Understanding the behavior, fate, and potential effect of MPs and NPs is crucial for assessing the potential health and environmental impacts. To conduct such assessments effectively, specific indicators like particle size, chemical composition, and toxicity levels should be analyzed. Methods such as spectroscopic analysis, bioassays, and ecotoxicological studies can provide valuable insights. Developing a successful remediation strategy depends mainly on the two major factors responsible for plastic prevalence in nature: physicochemical weathering and the formation of biofilms. Most often, the degradation of polymeric dental materials like resins is caused by salivary components, excessive chewing forces, oral microbe interaction, and thermal and pH changes within the buccal cavity leading to MPs/NPs release (Gupta et al., 2012; Tuncer et al., 2013; Wan Ali et al., 2018).

4.1. Saliva and mechanical friction

The dental products used to take care of oral hygiene and maintain good teeth structure are constantly under contiguousness with saliva and mechanical forces of both teeth and tongue while chewing. A study has confirmed the release of MPs from regular toothbrushing activity (Fang et al., 2023b). This raises concerns about the direct release of MPs in the digestive system. Products like dental fillings and orthodontic aligners reside within the buccal cavity until desired results are achieved, which increases their probability of releasing MPs/NPs. For example, the recently emerging, transparent, and easy-to-use tooth aligners in the market have gained huge customer attention because of their easy and painless installation. In a study, secondary MPs were identified unprecedently in orthodontic aligners under the influence of saliva. Two aligners from each group were placed in artificial saliva for seven days and stirred for 5 h each day to mimic the mechanical friction between teeth in the human body. The fluid containing the mixture of artificial saliva was filtered and the filtered particles were analyzed by SEM and Raman spectroscopy, which confirmed the release of microparticles under friction in the mouth (Quinzi et al., 2023). Bis-GMA is generally found in powdered form and as a result, they are separately polymerized during dental filling, which also leaves higher chances for the unpolymerized monomers to be left over in the patient's mouth. These were found to be dissolving in saliva, which was confirmed by competitive ELISA, thus concluding the release of MPs/NPs (Sasaki et al., 2005). Saliva interacts with dental RBCs by penetrating the polymer structure. This reaction leads to the release of unreacted monomers and additives. The subsequent degradation of the RBCs is influenced by factors such as the degree of curing, polymer network structure, and the specific monomers used. Poorly cured resins with exposed ester groups are particularly susceptible to breakdown by water and enzymes (Chandran et al., 2021; Ferracane, 2006).

Clinical procedures including RBCs generate microparticles. This occurs during the removal of old restorations and the shaping, or polishing of new ones. Microparticles are also generated during the laboratory fabrication of restorations from pre-polymerized RBCs (Van Landuyt et al., 2012). The size of these particles varies from nanoscale to approximately 10 μm (Mulligan et al., 2022). The interaction between dental materials and saliva, combined with mechanical forces during dental treatment leads to the release of MPs/NPs.

4.2. Bacterial attachment on micro/nanoplastic surfaces

The interactions between MPs/NPs and biofilm-forming microorganisms are complex. Initial research should prioritize understanding the mechanisms governing particle-microbe contact and attachment. As shown in Fig. 2**,** the resin is attached to teeth enamel with the aid of an adhesive put on the dentin. These resins are composed of various monomers as discussed above like PMMA, Bis-GMA, TEGDMA, etc. Oral microbes attach to these MPs/NPs surfaces, most of which interactions at the oral microbiome level are not well-established. There exists a lack of knowledge about the interaction between microplastic surfaces and microorganisms (Rummel et al., 2017). However, the possible mechanism of microbial interaction with MPs/NPs surfaces is via chemical adsorption, repulsive or attractive interactions, colonization, and ingestion (Lu et al., 2019). A few relevant parameters in the attachment process include surface topography, roughness, charge, free energy, hydrophobicity, and electrostatic interaction (Rout et al., 2022). In general, a key defense mechanism against the penetration of NPs into organisms is the bacterial membrane. Nanoplastic uptake, membrane damage, and nanoplastic transformation inside and outside of cells are all influenced by the type of interactions between nanoplastics and the membrane (Liu et al., 2023). The hydrophobicity of surface and polymer topography has no such effect on the bacterial attachment to the polymeric substrate (Hook et al., 2012). In the case of poly(meth)acrylates, there is a strong possibility of correlation between bacterial attachment with hydrophobicity and molecular flexibility of plastic surfaces (Bhagwat et al., 2021; Sanni et al., 2015). An *in vitro* study exposed resin-based restorative materials to three major oral microbes for instance, *Streptococcus mutans*, *Streptococcus oralis*, and *Actinomyces naeslundii* for 35 days and observed the thick biofilm formation on its surface within a few hours (Fig. 2). The study showed the active adherence of bacteria to the restorative material surface upon SEM and implied that the oral microbe growth release acids that can damage the polymers, releasing MPs (Willershausen et al., 1999). The degradation of

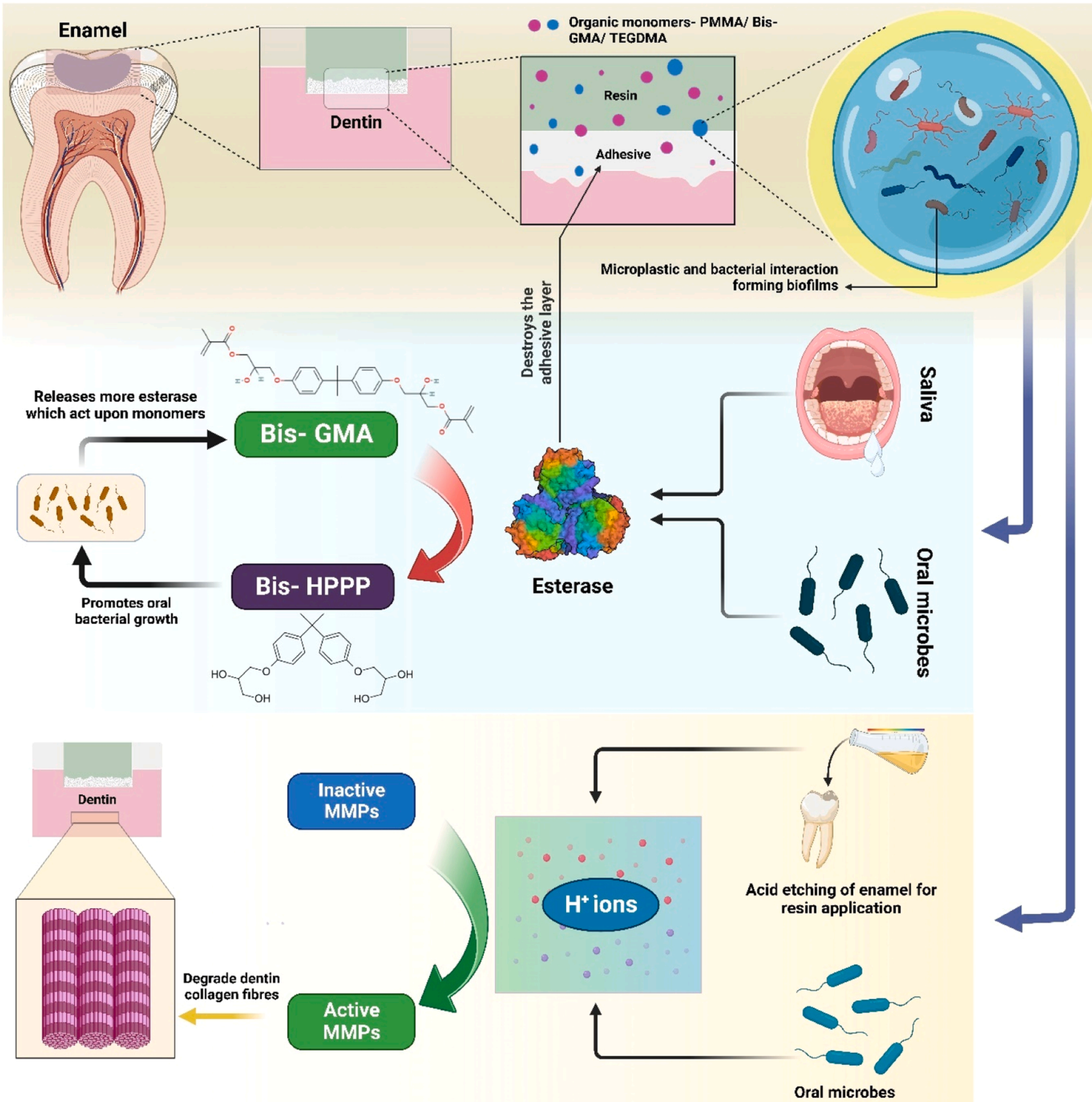

Fig. 2. Action of oral microbes on dental resin-based composites via esterase or creation of an acidic environment.

dental RBCs is enhanced by esterase released from saliva as well as oral bacteria, which degrades the ester bonds in dental resins resulting in monomer release. As depicted in Fig. 2, the esterase released from saliva and oral microbes either directly destroys the methacrylate present in adhesive, thus degrading it further to increase susceptibility to more bacterial attacks or hydrolyzes Bis-GMA to 2,2-Bis[4(2,3-hydroxypropoxy)phenyl]propane (Bis-HPPP), which also promote bacterial growth. The proliferation of bacteria releases more esterase to degrade the adhesive layer and the cycle continues, increasing the biodegradation of dental RBCs. The etching of tooth enamel as preparation for dental filling and the bacteria creates an acidic environment in the mouth, due to which H^+ ions activate inactive MMPs (matrix metalloproteinase), degrading dentin collagen fibers (Fig. 2) (Guo et al., 2022).

On the contrary, nanoplastic's interaction with oral microbiome is an untouched topic in research but general bacterial interactions have been explored quite well. The development of EPS (Extracellular Polymeric Substances) and its mechanism of regulation of NPs of different charges aggregated to interact by electrostatic and hydrophobic bonds with bacterial membranes were analyzed. EPS formed by bacteria interacts with nanoplastics irrespective of the charge through electrostatic repulsion combined with steric hindrance. Results showed that different species of bacteria, based on their charge and hydrophobicity, revealed distinct interactions with EPS assembly, either promoting or suppressing them. EPS inhibited cationic nanoplastics from adhering to bacterial membranes, by lowering the surface charge. Although neutral and anionic NPs displayed only weak membrane interaction and EPS increased their binding contacts (Liu et al., 2023). Deriving knowledge from these data, there is ample space for more research to be carried out on how charge-based NPs can be employed in the use of dental RBCs, to promote the growth of good oral microbe and suppress bacteria harmful to oral health.

4.3. Thermal change

Other potential factors responsible for MPs/NPs release are thermal changes resulting inside the oral environment due to the ingestion of various hot and cold food substances. Natural teeth have a different thermal expansion coefficient as compared to the dental materials used which can lead to creating an antagonistic environment. The *in vivo* thermal fluctuation can degrade the dental materials used by inducing surface stress as a result of the thermal gradient near the dental surface (Gupta et al., 2012). Nanofilled composites have been shown to decrease their shear and elastic modulus and are inversely proportional to the degree of temperature. In a study carried out to analyze viscoelastic properties of nanofiller composite dental materials, nanofiller composites at static and dynamic conditions were tested at 21°C (at dry state) and at 21°C, 37°C and 50 °C (at wet state), followed by one-way and two-way ANOVA analysis. The coefficient of decay dynamic viscosity along with specified damping increased with the rise in temperature from 21°C to 50°C (Papadogiannis et al., 2008).

4.4. Change in pH

While dental materials such as composite resins and acrylic resins are used to restore teeth and dental prostheses, these are constantly under the activity of tooth brushing, pH, and temperature change which causes undesirable influence on the dental material (Ahmed et al., 2022). The mouth cavity and teeth are consistently subjected to a wide range of physiological pH fluctuations, owing mostly to the type of food intake. Dental materials are also directly or indirectly degraded by the intraoral pH change by daily intake of food and drinks (Jepson et al., 2000). In dental caries treatment to limit plaque accumulation, the pH of the filling is an important factor that affects bacterial colonization (Lehmann et al., 2021). While chemicals with a low pH, high titratable capacity, and high buffering capacity have the most erosive power, substances with high Ca^{2+} ion and phosphate concentrations produce the least disintegration of the tooth surface and can improve its chemical stability and integrity (Saads Carvalho and Lussi, 2019). Although there is a significant improvement in the quality of dental composite materials, they are still prone to degradation, and discoloration, where incomplete polymerization is one of the main problems (Abed et al., 2015).

In an experiment conducted by Dipankara et al. the effect of toothbrushing activity was studied. The sample was equally divided between acrylic and composite resins. Under pH treatment, there was a significant release of MPs as compared to the samples exposed to brushing or temperature. The fact that acrylic and composite resins encountered weight loss, confirmed the release of microplastic, although the microplastic released is secondary (Dipankara et al., 2021). Another experiment performed to investigate the effectiveness of two different types of toothpaste (one with fluoride and one without) and a fluoride varnish in preventing erosion caused by an acidic environment present in the oral cavity, showed a change in the enamel surfaces because of the change in the acidic condition, increasing the roughness (Mazzoleni et al., 2023). The use of polymeric materials and resins has increased in dentistry because of desired biological properties and low-cost production. It is quite evident that polymeric material is released due to changes in pH in dental products which is harmful to human beings.

5. Impact on human

MPs/NPs released from various dental products, be it from a simple toothbrushing activity or even from dental fillings, are destined to end up in the human body irrespective of their source. As discussed above, the different types of MPs/NPs characterized by dental products have also shown detrimental effects on the human system.

5.1. Impact of micro/nanoplastics from toothbrushing activity

Potentially abrasive toothpaste formulated with polyethylene microbeads is commonly used to remove surface stains from teeth, which has been shown to wear down the enamel or the top coating of the teeth (Ganss et al., 2016). Microbeads exert an abrasive force on teeth via a physical mechanism. These polyethylene particles induce mechanical wear on the tooth surface. The brushing pressure amplifies this effect, driving the microbeads against the enamel and causing gradual damage to the crystal structure. The irregular morphology of the beads enhances their abrasive capacity (Baig et al., 2020; Enax et al., 2023; Guzik et al., 2023). This leads to cumulative damage of enamel over time. The disruption of enamel's structure creates irregular surface patterns. The resulting surface irregularities increase susceptibility to staining and bacterial adhesion (Ustabasi and Baysal, 2019; Ustabasi and Baysal, 2020). Toothbrushes used worldwide are composed of biocompatible plastics and thus bear the most probability of releasing MPs/NPs, but no concrete research has established the mechanism of MPs/NPs released from the frictional activity while toothbrushing, which eventually ends up in the system. MPs, originating from toothpaste or toothbrush erosion, can be inadvertently consumed. The ingestion of these particles has been linked to a range of adverse health outcomes, such as inflammation, potential toxic effects, and increased risk of diabetes, heart diseases, as well as impaired immunity (Chengappa S et al., 2023; Hirt and Body-Malapel, 2020; Li et al., 2023; Song et al., 2016; Trasande et al., 2022). NPs, in particular, due to their diminutive size can traverse biological barriers and infiltrate the bloodstream. Long-term exposure to MPs/NPs, even at minimal levels has been linked to reproductive and developmental abnormalities (Li et al., 2023). MPs can interfere with the rheological properties of saliva, thereby influencing oral health dynamics (Przekop et al., 2023). Studies have correlated elevated saliva viscosity with an increased susceptibility to periodontal disease and dental caries (Biesbrock et al., 1992; Radhi and Yas, 2013). Altered salivary viscosity could lead to reduced bacterial co-aggregation and impaired oral clearance. This may increase the risk of conditions like aspiration pneumonia and cardiovascular disease, particularly in the elderly (Kitada and Oho, 2012).

5.2. Impact of micro/nanoplastics from dental resin-based composites

RBCs are versatile, used for both direct and indirect restorations, and cements and to conserve tooth structure due to their adhesive properties (Chesterman et al., 2017; Ferracane, 2011). RBCs composed of various materials such as Bis-GMA, UDMA, and TEGDMA, can generate MPs through processes like monomer degradation, mechanical wear, and incomplete polymerization. These MPs may pose significant health risks, particularly given their potential for ingestion, and inhalation. While it is established that monomeric constituents of RBCs exhibit cytotoxic and genotoxic properties at elevated concentrations, the full extent of their impact is unknown (Urcan et al., 2010; Wada et al., 2004; WATAHA et al., 1994).

5.3. Effects of poly (methyl methacrylate)

PMMA has shown excellent biocompatibility properties as already discussed above but poses a threat to the oral environment when unpolymerized MMA monomers fail to form PMMA and get released into the saliva from dental fillings (Cebe et al., 2015; Michelsen et al., 2012). Small, hydrophilic unpolymerized MMA monomers and other lightweight substances generated during the polymerization process may diffuse over the residual dentin layer in case of deep cavities and trigger adaptive pulp cell responses at that point (Fujisawa and Atsumi, 2004; Zhang et al., 2019). Additionally, research has demonstrated that cells exposed to MMA monomers generated more ROS while also producing lesser intracellular reduced glutathione (Krifka et al., 2013). These results suggest that MMA monomer exposure may be a trigger point for the development of cellular oxidative stress. When ROS levels are high enough, they can overwhelm cellular antioxidants, causing oxidative stress to lead its way into oxidative attacks on crucial cellular macromolecules including proteins, lipids, and DNA (Ilea et al., 2018; Jiao et al., 2016). DNA damage due to MMA monomer exposure to the patient's gingival fibroblasts occurred after 6 h of incubation (Szczepanska et al., 2012). Histone H2AX phosphorylation to γ-H2AX at DNA damage sites is a preliminary stage in developing the cellular response to DNA double-strand breaks. In cells exposed to an MMA monomer resin, experimental findings show that H2AX phosphorylation is a sign that DNA double-strand breaks are forming (Urcan et al., 2010).

Recent research has explored the effects of PMMA NPs on BHK-21 cell lines, revealing several important findings (Mahadevan and Valiyaveettil, 2021). PMMA NPs were found to be taken up by cells via endocytosis, accumulating in the cytoplasm but not penetrating the nucleus. Exposure to these NPs caused a dose-dependent reduction in cell viability, with 61.3 % viability after 120 h. Additionally, PMMA NPs led to decreased ATP production and increased levels of ROS. Another study explored the toxic effects of PMMA microparticles on human liver cells using the HepG2/THP-1 macrophage co-cultured model (Boran et al., 2024). PMMA exposure led to increased ROS production, lipid peroxidation, and oxidative DNA damage. Inflammatory responses were marked by the upregulation of several pro- and anti-inflammatory cytokines, with NFκβ activation indicating a robust inflammatory reaction. PMMA MPs affected key genes involved in lipid metabolism such as FABP1, PPARγ, PPARα, LXR-α, and LDLR, leading to alterations in lipid balance and membrane integrity. TEM analysis revealed an increase in lipid droplets and polar lipid accumulation. PMMA MPs, measuring 3–10 μm, adhered to cell membranes, possibly causing mechanical damage and further contributing to oxidative stress and inflammation.

5.4. Effects of bisphenol A-glycidyl methacrylate

Bis-GMA can lead to BPA formation, making it the most potentially harmful to human health. In the oral cavity, the pliability of the Bis-GMA matrix enhances solvent penetration and subsequent expansion of the polymer network. This promotes the sustained diffusion of residual monomers (Finer et al., 2004; Finer and Santerre, 2004). The monomer Bis-GMA inhibits odontogenic differentiation of human dental pulp stem cells by suppressing dentin-related gene expression and alkaline phosphatase activity (Schneider et al., 2019). Unpolymerized Bis-GMA severely damages the surrounding gingival epithelium. This damage facilitates bacterial invasion into the underlying connective tissue, initiating inflammation and subsequent destruction of the tooth's supporting structures. This is an early stage of periodontal disease. Within the first few days of placement, approximately 8–10 % of unreacted Bis-GMA is released, exhibiting toxic effects on multiple cell types (Chang et al., 2010, 2009; Engelmann et al., 2004; Gniadek and Dąbrowska, 2019; Li et al., 2012; Willershausen et al., 1999; Yano et al., 2011). A study elucidates the mechanisms underlying the cytotoxic effects of Bis-GMA. The findings indicate that Bis-GMA induces apoptosis and G1 cell cycle arrest in human oral keratinocytes primarily through the accumulation of intracellular ROS. Furthermore, they identified the involvement of mitochondrial dysfunction and alterations in the P13K/Akt signaling pathway in cytotoxic response to Bis-GMA (Zhu et al., 2015).

The leaching of BPA from dental materials is also due to the incomplete polymerization process (Fleisch et al., 2010). BPA has been related to interfering with the immune system, producing diabetes mellitus, participation in cardiac degeneration, an increased risk of cancer, interfering with spermatogenesis leading to male infertility, and is directly linked to PCOS, nephrotoxicity, and thyroid dysfunction (Della Rocca et al., 2023). BPA, after being processed by the liver, is primarily eliminated through urine in the form of bisphenol A glucuronide. Its phenolic nature enables it to bind with estrogen receptors and act as either an agonist or antagonist through estrogen receptor-dependent signaling pathways. This capacity makes BPA a factor in the development of various disorders like male and female infertility, precocious puberty, hormone-dependent tumors including breast and prostate cancer, and metabolic disorders like polycystic ovary syndrome (PCOS) (Zoeller et al., 2005). The regulation of male reproduction, such as spermatogenesis, is governed by a key regulatory element known as the androgen receptor. Research has shown that BPA behaves as an antagonist of the androgen receptor, impacting cell signaling, function, and development in this area (Bonefeld-Jørgensen et al., 2007; Xu et al., 2005).

5.5. Effects of urethane dimethacrylate/ triethylene glycol dimethacrylate

Materials like UDMA polymer have been shown to continue to release monomers even after they have been polymerized or cured, which may have implications for biocompatibility and patient safety (Ginzkey et al., 2015). Unbound UDMA, a primary component released from dental adhesives and RBCs can induce adverse reactions in surrounding tissues. This leakage hinders healing and causes inflammation and necrosis within the dental pulp (Silva et al., 2006). In an investigation, it was observed that UDMA exhibited a concentration-dependent cytotoxic effect on RAW264.7 macrophages. It induced early apoptosis at lower concentrations and progressed to late apoptosis at higher exposures. The underlying mechanism of UDMA-induced cytotoxicity involved DNA damage, activation of caspases 3, 8, and 9, mitochondrial dysfunction, and elevated intracellular ROS. This suggests that UDMA released from the dental composites may contribute to macrophage impairment, with implications for potential immune dysfunction.

TEGDMA, a diluent commonly used in the production of RBCs alongside Bis-GMA, has been found to pose risks in terms of biocompatibility and possible toxicity. HPLC analysis has determined that TEGDMA is the primary monomer released from dental composite resins during experimentation. At concentrations present in these resin-based composites, TEGDMA is toxic to monolayer cell cultures of epithelial cells. *In vitro* studies on human oral mucosal models have demonstrated that experimental resin-based composites that contain increased levels of TEGDMA cause significant mucotoxicity and result in an elevated amount of the inflammatory cytokine IL-1 being released from oral mucosal models (Moharamzadeh et al., 2008). TEGDMA monomers showed cytotoxicity through the induction of apoptosis, inflicting genotoxic effects, and retarding the cell cycle process (Krifka et al., 2013).

5.6. Effects of hydroxyethyl methacrylate

In comparison to other matrix monomers like Bis-GMA, UDMA, and TEGDMA, HEMA exhibits superior penetration into the hybrid layer. The enhanced diffusion is attributed to HEMA's molecular sieve properties. This facilitates interaction with both collagen fibers within dentin and hydrophilic/hydrophobic components of the resin (Sun et al., 2018). HEMA has been demonstrated to disrupt cell growth and cause cell toxicity in a variety of cell types. The depletion of intracellular glutathione (GSH) levels is one way by which HEMA causes cell damage. GSH deficiency can result in the development of ROS, which are extremely reactive molecules capable of causing oxidative damage to biological components such as lipids, proteins, and DNA (Morisbak et al., 2015).

5.7. Effects of micro/nanoplastics after ingestion

The gut microbiota plays significant regulatory roles in the immune system by breaking down proteins and complex carbohydrates which creates metabolic byproducts, thus helping in communication between the gut epithelium and immune cells (Yoo et al., 2020). A correlation exists between gut dysbiosis and immune dysregulation, which increases the likelihood of developing various diseases such as diabetes, autoimmune disease, cardiovascular disease (CVD), and inflammatory bowel disease (IBD) (Miele et al., 2015; Sanz et al., 2010). Microplastics comprise a mixture of harmful chemicals that can pose a threat to human cells and the microbial community in our digestive tract, also known as the gut microbiome (Prata et al., 2020). The primary ways in which MPs are taken up are through phagocytosis and endocytosis. It is also possible for MPs to enter the lymphatic system by traveling through the circulatory system in mammals (Çobanoğlu et al., 2021). The MPs can move to different parts of the human body and stimulate a targeted immune response in that area (Cox et al., 2019). The M cells (Microfold cells) in Peyer's patches found in the ileum are the primary locations for the uptake and translocation of particles within the gastrointestinal tract

(Powell et al., 2010). MPs can knead through junctions in the single-layer epithelium and seep into the underlying tissues, which are captured by the dendritic cells and transported into the adjacent lymphatic and circulatory systems (Fig. 3a) (Lett et al., 2021; Oßmann, 2020). If MPs accumulate in this compartment, it may disrupt the normal route for absorbing endogenous microparticles, which can mess with the immune system's ability to detect and fight off foreign substances, ultimately weakening local immunity (Wright and Kelly, 2017). In the small intestine epithelium, macrophages bind to MPs/NPs with their Tim4 receptor via aromatic interactions (Fig. 3b) and use phagocytosis to absorb particles larger than 0.5 μm, whereas honeycomb cells use endocytosis to internalize 5 μm of particles (Kuroiwa et al., 2023; Revel et al., 2018). The entry of microplastics into macrophages by phagocytosis induces a shift towards the glycolytic pathway and reduces respiration in mitochondria, thus macrophages cannot break down MPs (Merkley et al., 2022). Macrophages ingest polystyrene microplastics hampering mitochondrial kinetics, thus activating autophagy of mitochondria and lysosomes (Fig. 3b) (Yin et al., 2023). This cellular metabolism shift affecting various gastrointestinal metabolisms remains unclear. Another investigation demonstrated the ineffectiveness of microparticle excretion when 0.3 % of MPs given orally to rodents found their way to enter the epithelium (Bouwmeester et al., 2015). For instance, after a five-day oral course of 60 nm polystyrene nanoparticles in rats, 10 % of the dose was discovered in the gastrointestinal tract, which stressed the fact that microplastics remain affixed to the apical areas of intestinal epithelial cells rather than being digested. This behavior might have an impact on the local immune system and cause intestinal inflammation (Hirt and Body-Malapel, 2020).

6. Fate of released micro/ nanoplastics in the environment

A wide variety of MPs/NPs used in dentistry are absorbed into the human system as already discussed in the previous section, but instances have shown some microplastics to be excreted out as well. A preliminary study examined urine samples from six volunteers in Italy. By employing Raman microspectroscopy, the researchers detected various types of microplastics, including polyethylene (PE) and polypropylene (PP). These findings suggest that MPs can traverse the gastrointestinal tract and be eliminated through biological processes (Pironti et al., 2023). This indicates a complex interplay between absorption and excretion of microplastics within the human body. Another study found that MPs can enter the bloodstream and be detected in both blood and urine within 4 h after injection in mice. Using fluorescence signatures, researchers tracked MPs following tail vein, oral, or pulmonary administration (Sun et al., 2022). Kidney excretion might be a way to eliminate NPs, as the kidney filter typically only allows particles smaller than 10 nm (Feng et al., 2018; Jiang et al., 2019). However, MPs could potentially pass through the kidney tubules. This might happen through processes like exocytosis and endocytosis near the tubular cells after MPs leave the kidney filter and enter the peritubular capillaries (Deng et al., 2019;Sun et al., 2022). Methacrylate, its polymer, and polyelectrolytes are the building blocks of dental polymer materials such as resins (Lönnroth and Shahnavaz, 1997). It is generally established that after dental treatments using RBC, released monomers of the dental composite are discharged into the environment through human excretion since they can be found in saliva and urine (Kingman et al., 2012; Sasaki et al., 2005). The restorative RBCs frequently used in dentistry can produce significant environmental damage, depending on their lifecycle (Mulligan et al., 2018). RBC restorations that have been used to repair a tooth, leak unpolymerized monomer in the mouth at noticeable levels for months after they have been installed (Polydorou et al., 2009). When these materials are shaped, finished, and polished after being placed on or removed from teeth, particulates and microparticles comprising part polymerized monomer are discharged into wastewater. The excess unused or expired RBCs treated as municipal solid waste, also eventually end up in the landfill sites. The major primary pollution occurs when waste from RBC manufacturing units is dumped in landfills. The putrefaction of waste in landfills caused by microbial degradation of organic matter produces leachate. The leachate consisting of organic and inorganic matter, xenobiotic compounds, and heavy metal ions when subjected to certain physical parameters like pH, temperature, and oxygen content tends to change its reactivity over a period. This reactive leachate when interacts with RBCs, makes RBCs break down into several components such as monomers, oligomers, and BPA (Mulligan et al., 2022).

These individual components may end up in the environment due to several factors like the disruption of landfill liners, coastal landfill erosion processes, and other natural disasters like flooding. Through computational modeling, the United States Environmental Pollution Agency (USEPA) Office has suggested that potential environmental contamination from dental composites is likely to occur through unintentional release during transportation. To mitigate these issues incineration of RBCs can be adopted, although incineration itself releases particulate matter, metals, acid gases, and other substances which again become a significant threat to public and environmental health (Sharma et al., 2013). The more the number of free monomers higher will be the pollution. So, the degree of polymerization should be kept in check. In that case, the CAD/CAM milling process should produce more highly polymerized RBC than conventional methods and should be used as a better approach but isn't any good for the environment as the milling process huge amounts of microparticle powder waste.

These MPs end up in water bodies through municipal wastewater and affect different life forms. It has been found that these MPs tend to bind to other contaminant toxins found in the environment (Joo et al., 2021). MP particles form conjugates with these biotoxins known as persistent organic pollutants (POPs) such as polychlorinated biphenyl (PCB), which cause havoc in the environment (Engler, 2012). These conjugate compounds enter the food chain when they are consumed by smaller organisms, which get accumulated in the bodies of such organisms through bioaccumulation and climb up the food chain to biomagnify (Fig. 4) (Cole et al., 2011). The development, reproduction, motility along with survivability of aquatic species can be affected by additives released from these microplastics, such as BPA. At even lower concentrations, the negative effects of this known endocrine disruptor of aquatic organisms can be seen. The severity of effects ranges from systemic to molecular levels (Wu and Seebacher, 2020). Dental restorative materials and adhesives begin to set chemically when two components are mixed or when light is applied. In both cases, due to incomplete polymerization, unreacted monomers are released (Lönnroth and Shahnavaz, 1997). These monomers not only get excreted out but also affect the human body, possibly leading to various diseases. Table 2 provides an overview of the various sources of microplastics (MPs) and nanoplastics (NPs) in dental care products, along with their potential health effects and environmental pathways.

7. Future perspective

The widespread use of MPs/NPs in dentistry and their toxic effects have been investigated through various research both *in vivo* and *in vitro*. Despite numerous research, plenty of gaps exist in this area. A key concern is the toxicological impact of MPs at the molecular and cellular levels. Although some studies have identified MPs in dental products, comprehensive research on their interactions with biological systems remains limited. Understanding their toxicity is challenging due to the wide variety of MP sizes, shapes, and chemical compositions. Subsequent research should focus on *in vitro* studies with human cell lines to evaluate MP cytotoxicity and examine molecular pathways impacted by exposure, including oxidative stress and inflammation. Future studies should explore how MPs from dental products affect freshwater and terrestrial organisms, with long-term evaluations to assess their accumulation and impact. There has been a debate in the field of dentistry about the potential correlation between leftover plastic microbeads in

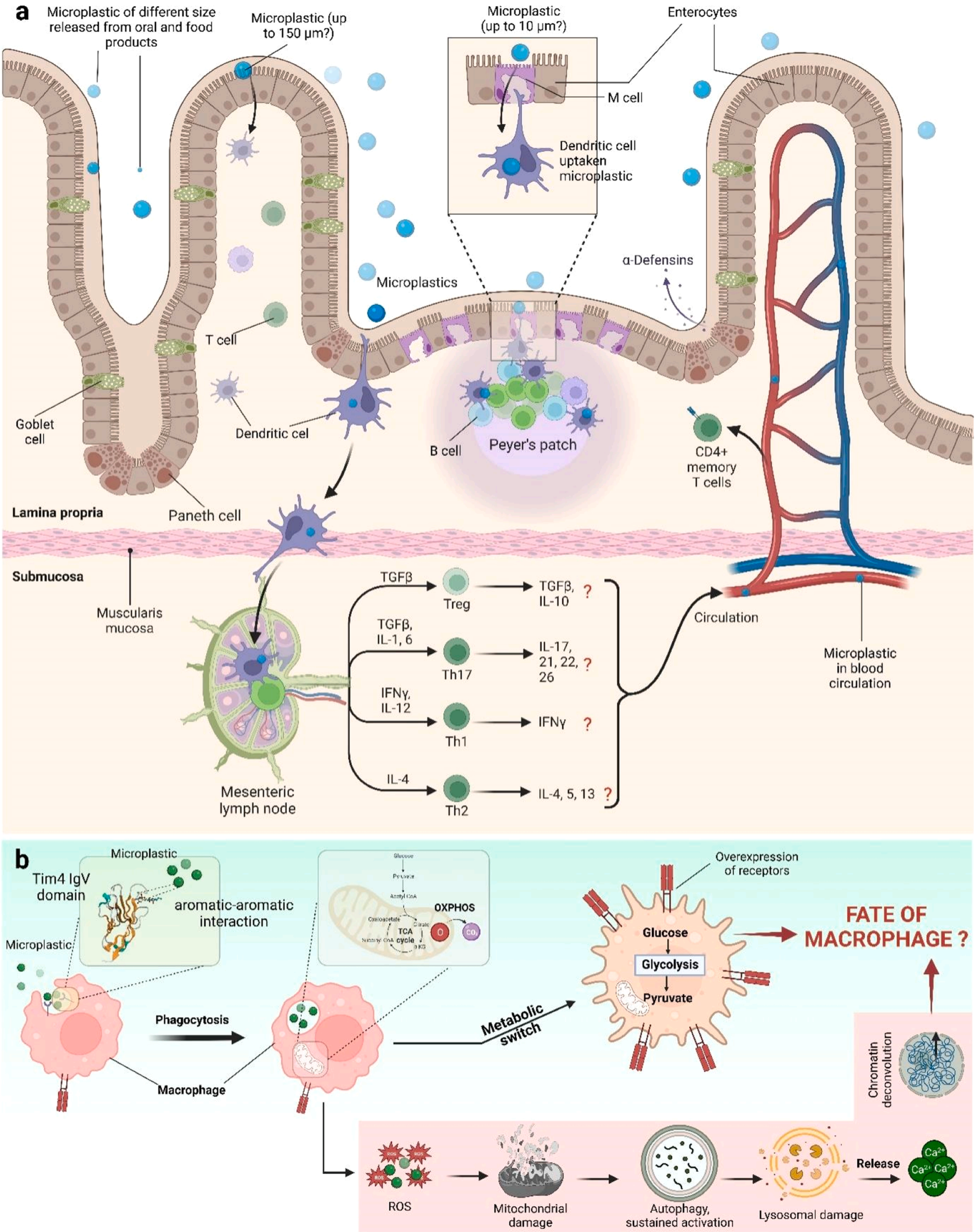

Fig. 3. Effects of MPs/NPs post-ingestion (a) Probable mechanism of microplastic ingestion in gastrointestinal tract. (b) Interaction between microplastic and macrophages results in metabolic switch regulation and ROS production.

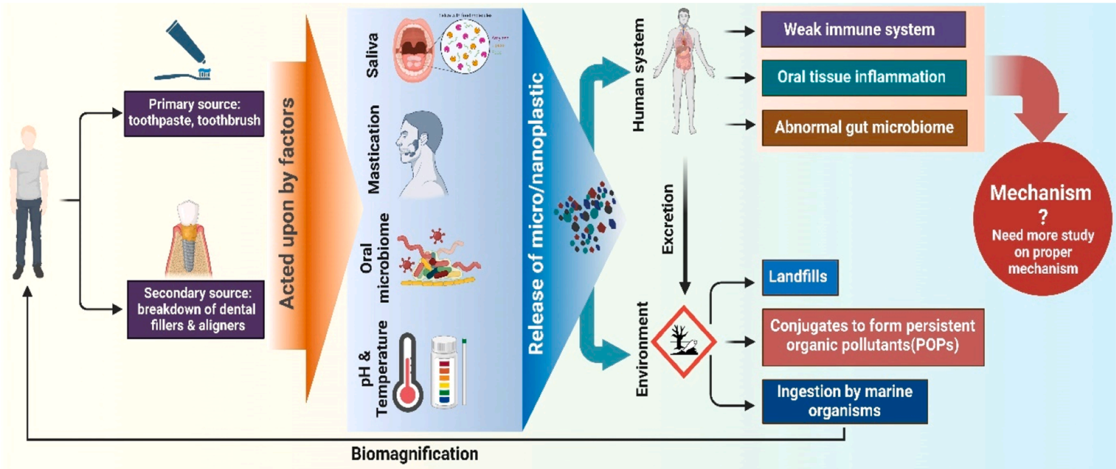

Fig. 4. Release of MPs/NPs from dentistry either directly into the human system or via release of MPs/ NPs found in the environment.

Table 2
Sources of micro/nanoplastics (MPs/NPs) from dental care products, their potential health impacts, and environmental pathways.

Source	Type of MPs/NPs	Potential Health Impacts	Environmental Pathways	Ref.
Toothbrushing Activity	Polyethylene	- Enamel wear and structural damage due to abrasion. - Ingestion of the released microparticles is linked to impaired immunity.	- MPs released during toothbrushing may enter wastewater systems. - Potential accumulation in aquatic ecosystems.	(Dipankara et al., 2021; Fang et al., 2023b).
Toothpaste with Microbeads	Polyethylene	- Oral health impacts: altered salivary viscosity increasing risks of periodontal disease and caries.	- Washed away into wastewater, leading to potential bioaccumulation in aquatic organisms.	(Ustabasi and Baysal, 2019); Ustabasi and Baysal, 2020)
Dental Resin-Based Composites (RBCs)	Bis-GMA, UDMA, TEGDMA, PMMA	- Acts as an endocrine disruptor by binding to estrogen receptors. - Cytotoxic effects on oral tissues and delayed healing.	- Enter the environment through improper disposal of dental materials. - Improperly cured fillings release PMMA into saliva; enter into the gastrointestinal tract, which may ultimately enter sewage systems and persist in water bodies.	(Kingman et al., 2012; Mulligan et al., 2018; Mulligan et al., 2022).

gum crevasses and periodontal disease. However, there is currently no solid evidence to support this claim. Exposure to MPs/NPs can harm the oral microbiome by reducing the diversity of beneficial bacteria and increasing the abundance of bacteria associated with gum disease. This can lead to a higher risk of pathogenic bacteria. Despite ongoing research, the exact mechanisms by which MPs affect the oral microbiome remain unexplored. While studies have identified the presence of plastic particles in various types of toothpaste, further research is essential to explore safer alternatives that prioritize human health. Moreover, the long-term health effects of MP exposure are largely unknown. While acute studies exist, data on chronic exposure to dental products is limited. Resource-intensive, longitudinal studies are needed, with epidemiological research and animal models to track health outcomes over time. Various eco-friendly toothbrush substitutes can be aimed to be developed by manufacturers. The bamboo used in most environmentally friendly toothbrush handles is more antibacterial than other substitute materials ("Anti-mold and hydrophobicity of cutinized bamboo prepared via different annealing processes," n.d.; Biria et al., 2022; Lyne et al., 2020). Identifying eco-friendly bristles could be difficult, as there are no current options that are both biodegradable and vegetarian. Moreover, it is to be highlighted that more research on MPs in dentistry has been conducted as compared to NPs, despite their toxicity being at a higher range ("Nanoplastics are significantly different from microplastics in urban waters," n.d.). Although short-term clinical studies have shown that the usage of nanocomposites is effective after 1 and 2-year follow-ups, long-term clinical trials are required to support this (Ernst et al., 2006; Schirrmeister et al., 2006). Dentists are also unaware of the proper installation and disposal of dental resins, which results in occupational asthma and MP accumulation in the environment. Thus, proper awareness among dental practitioners is a necessity, with revised rules and regulations to control such malpractice. The making of organic toothbrushes, toothpaste, or aligners should be given more attention, with reasonable prices at a huge production rate to make them easily available to the population worldwide. With careful observation and investigations to reduce or inhibit MPs/NPs use in dentistry, oral health, and hygiene will be safe and sound for human application, maximizing its designated benefits with the least side-effects in the future.

8. Conclusion

The ubiquitous presence of plastics within dental products poses a significant threat to both human health and the environment. The durability and aesthetic appeal of these materials have contributed to their widespread use. However, their lack of biodegradability and potential toxicity necessitates urgent action. Unfortunately, MPs/ NPs discovered in all kinds of dental products ranging from toothpaste to dental implants showed detrimental effects on humans. These MPs/ NPs have been linked to various health issues, such as hormonal imbalances and reproductive problems. As a result, there has been a push for more stringent regulations on the use of MPs/NPs in dental products to protect public health and safety. Researchers are also looking into alternative materials that can be used in dental products to reduce the risks associated with MPs/NPs. Some recent studies have been effectively carried out in pursuit of better alternatives.

A study considering the toxicological effect of amelioration by an antioxidant agent N-acetylcysteine (NAC) on dental pulp cells, cultured on PMMA-based resin, implied better physiological effects compared to the non-treated pulp cells cultured on the dental resin. The findings suggested that the incorporation of NAC into the resin can restore dental pulp cells' reduced cell viability and entirely suppress the phenotype of the odontoblast-like cell to a medically significant level (Kojima et al., 2008). The addition of bis (2,6-diisopropylphenyl) carbodiimide (CHINOX SA-1) further improved the hydrolytic stability of composites based on UDMA/ Bis-GMA/ TEGDMA monomers, which could potentially extend the service life of the modified material. Extended studies are needed to confirm the possible use of CHINOX SA-1 as an anti-hydrolysis agent in dental composites (Szczesio-Wlodarczyk et al., 2023).

Addressing the issue of microplastic and nanoplastic (MP/NP) pollution in oral care products necessitates a multi-pronged strategy involving dentists, manufacturers, policymakers, and researchers. Dentists, as trusted health professionals, play a pivotal role in raising awareness. By educating patients about the health and environmental risks of MPs/NPs and promoting the use of eco-friendly alternatives, they can inspire informed choices and sustainable oral care habits. This can drive demand for safer products and reduce reliance on harmful materials. Manufacturers must prioritize developing biodegradable alternatives, improving transparency in material use, and minimizing plastic emissions throughout the product lifecycle. Policymakers can support these efforts by enforcing stricter regulations, incentivizing sustainable innovations, and fostering interdisciplinary collaborations. Advancements in dental techniques, such as optimizing monomer-to-polymer conversion and adopting improved curing technologies, can minimize harmful particle release, enhancing material stability and patient safety. Proper waste management practices, including filtration systems in clinics and efficient recycling protocols, are essential to reduce environmental contamination and recover valuable resources.

In addition, public awareness campaigns and collaborative initiatives can accelerate the adoption of these measures. Investing in research to understand the toxicological impacts of MPs/NPs and the development of environmentally friendly alternatives will provide long-term solutions to this pressing issue. By collectively embracing these strategies, the dental community can substantially reduce the adverse effects of microplastic pollution. This transformation not only safeguards human health but also upholds the sector's responsibility toward environmental sustainability, contributing to a healthier planet and a more resilient future.

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CRediT authorship contribution statement

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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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Data availability

Data will be made available on request.

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