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Chitosan-Based Innovations for Microplastic Mitigation in Dentistry: Environmental Impact, Technological Advancements, and Future Perspectives: A Comprehensive Review

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Abstract

Microplastic pollution has become a critical environmental concern, with dentistry contributing significantly through plastic-based materials, personal care products, and improper clinical waste management. Chitosan, an abundant, biodegradable, and highly adsorptive biopolymer, offers a promising solution for mitigating microplastic pollution in dental practices. This review explores the potential of chitosan as an alternative adsorbent for microplastics, emphasizing its ability to bind electrically charged and polar microplastics through electrostatic interactions and hydrogen bonding. Implementing chitosan-enhanced filtration systems in dental wastewater treatment could substantially reduce the release of microplastics from dental practices. Additionally, this paper addresses the challenges associated with adopting chitosan-based technologies, including scalability and regulatory hurdles. It underscores the need for innovative approaches to improve sustainability in dental waste management.

Keywords: *Microplastics, Dentistry, Chitosan, Environmental Pollution, Waste Management*

I. Introduction

Microplastic pollution, a pervasive environmental issue, has become a significant concern due to its widespread presence in aquatic, terrestrial, and atmospheric environments. These particles, categorized as primary microplastics, which are directly produced, and secondary microplastics, which result from the degradation of larger plastic items, originate from sources such as industrial abrasives, personal care products, and the breakdown of larger plastics due to weathering and biological action (1,2). Dentistry contributes notably to microplastic pollution through plastic-based materials, including composites, sealants, and impression materials, which degrade over time, releasing fibers and fragments into the environment (3). Disposable dental items such as gloves, floss picks, masks, and suction tips, primarily made from polyethylene and polypropylene, further exacerbate this issue, mainly when improperly disposed of (4). Routine dental procedures, including polishing and cleaning, release microplastics from polymer-based abrasives into wastewater or as airborne particles, posing occupational and environmental hazards (5). Dental wastewater, often containing high loads of microplastics, challenges conventional treatment systems, allowing particles to infiltrate aquatic ecosystems, where they threaten biodiversity and act as carriers for persistent organic pollutants (6). These microplastics disrupt nutrient cycling in soil, inhibit plant growth, and accumulate in food chains, leading to structural damage, hormonal imbalances, and reproductive impairments in aquatic species while also affecting human health through ingestion or inhalation (7,8). To mitigate this, chitosan, a biodegradable biopolymer, offers promising solutions through its ability to adsorb microplastics via electrostatic interactions and hydrogen bonding. This approach can be integrated into filtration systems for dental wastewater management, effectively capturing up to 90% of microplastics and significantly reducing environmental contamination (9). However, challenges such as scalability, production costs, and regulatory barriers remain, necessitating comprehensive policies and financial incentives to promote sustainable practices in dentistry (10,11).

Microplastic pollution, a pervasive environmental issue, poses significant threats to aquatic and terrestrial ecosystems and human health. Dental practices contribute to this issue by using plastic-based materials, such as composites, sealants, and disposable items, which degrade into microplastics over time and infiltrate wastewater systems. These microplastics disrupt aquatic ecosystems by being ingested or absorbed by organisms, causing hormonal imbalances, structural damage, and amplification along the food chain (12,13). Microplastics alter soil structure and nutrient cycling in terrestrial environments, affecting plant growth and microbial communities (14,15). Health risks associated with microplastic exposure include inhalation, ingestion, or dermal contact, leading to inflammation, oxidative stress, and potential toxicity in multiple body systems (16,17). Microplastics also serve as vectors for persistent organic pollutants, exacerbating their harmful effects on humans and the environment (18,19). Chitosan, a biodegradable polymer, has shown promise in mitigating microplastic pollution through adsorption via electrostatic interactions and hydrogen bonding, capturing up to 90% of microplastics in wastewater (20,21). However, challenges such as cost, scalability, and regulatory approval remain, necessitating comprehensive policies and incentives to promote sustainable practices in dentistry (22,23).

II. Review

Microplastic pollution has become a pressing environmental issue, with dentistry contributing significantly through plastic-based materials and consumables. Chitosan, a natural biopolymer derived from chitin, offers immense potential for addressing this issue due to its unique properties, including biodegradability, high adsorption capacity, and cationic nature, which enables it to bind effectively with negatively charged pollutants such as microplastics (24). Research has demonstrated the versatility of chitosan in wastewater treatment and pollution control, particularly for removing microplastics from dental wastewater. Advanced forms of chitosan, such as nano-chitosan, exhibit enhanced adsorption efficiency due to their increased surface area and reactivity, making them practical for capturing even trace amounts of microplastics in dental settings (25).

Chitosan-based filters, incorporating chemically modified chitosan or hybrid systems, provide promising solutions for microplastic remediation. These systems utilize chitosan's electrostatic binding properties to achieve high retention rates of microplastics, with efficiencies reaching up to 90% in laboratory settings (26). Integrating chitosan with other materials, such as graphene oxide, magnetic nanoparticles, bentonite clay, and carbon nanotubes, further enhances its adsorption capabilities, stability, and versatility in complex wastewater treatment scenarios (27-29). Additionally, smart chitosan-based materials responsive to environmental stimuli such as pH or temperature are emerging as innovative solutions for targeted filtration in dental wastewater management (30).

However, despite the promising attributes of chitosan-based technologies, challenges remain. These include high production costs, scalability issues for large-scale applications, and the lack of comprehensive regulatory frameworks to support their adoption in dental practices. Addressing these challenges requires a multidisciplinary approach, combining advances in material science, policy development, and financial incentives to facilitate the transition to sustainable practices (31, 32).

Microplastic pollution has become a pressing environmental issue, with dentistry contributing significantly through plastic-based materials and consumables. As detailed in **Table 1**, sources of microplastics in dentistry include composite resins, orthodontic adhesives, impression materials, and disposable items such as gloves, masks, and floss picks. These materials degrade over time, releasing microplastics into water systems, soil, and even air during dental procedures. This persistent pollution underscores the urgent need for innovative and sustainable solutions within the dental field.

Table 1. Sources of Microplastics in Dentistry

No.	Dental Source	Plastic Polymer Type	Microplastic Generation Process	Environmental Impact
1	Composite Resins	Polyurethane, Polyethylene (PE)	Wear and tear during restorative use	Persistent microplastics in wastewater, resistant to degradation
2	Orthodontic Adhesives	Polypropylene (PP), Polyethylene (PE)	Fragmentation during mechanical stresses	Releases microplastics into the environment post-application
3	Sealants and Coatings	Polyethylene Terephthalate (PET)	Slow degradation over time	Microplastics leach into soil and aquatic systems
4	Impression Materials	Polyvinylsiloxane, Polyether	Breaks down after clinical use	High persistence in landfills, contributing to soil contamination
5	Disposable Gloves	Polyethylene (PE), Nitrile	Fragmentation in landfills	Adds to microplastic load in terrestrial ecosystems
6	Single-use Floss Picks	Polypropylene (PP)	Discarded post-use; fragments in the environment	Widely used in dental hygiene, adding to landfill plastic waste
7	Polishing Pastes and Air Abrasives	Polystyrene (PS), Polyethylene (PE)	Released during dental procedures; enters wastewater	Pollutes water systems; airborne particles pose inhalation risks

8	Plastic Suction Tips	Polyethylene (PE), Polypropylene (PP)	Breaks down during disposal	High microplastic content in dental wastewater
9	Disposable Masks and Syringes	Polypropylene (PP), Polystyrene (PS)	Fragmentation post-disposal	Masks contribute significantly to clinical waste
10	Dental Cups and Trays	Polypropylene (PP), Polystyrene (PS)	Decomposes in landfills	Single-use items increase the plastic burden in waste streams
11	Sterilized Packaging for Dental Instruments	Polyethylene Terephthalate (PET)	Improper disposal leads to microplastic formation	Commonly contributes to landfill microplastic accumulation
12	Plastic-based Restorative Materials	Polyethylene (PE), Polyvinyl Chloride	Release during clinical use	Persists in water systems, challenging to biodegrade
13	Plastic Braces and Aligners	Polypropylene (PP), Polycarbonate	Abrasion over time	Orthodontic devices release microplastics into wastewater
14	Discarded Plastic Dental Instruments	Polypropylene (PP), Polystyrene (PS)	Degrades over extended periods in landfills	Low recycling rate increases environmental plastic load
15	Plastic Toothbrushes and Cleaning Aids	Polypropylene (PP), Polyethylene (PE)	Wear and tear from usage and improper disposal	Contributes to terrestrial and marine microplastic pollution
16	Dental X-ray Films and Packaging	Polyethylene (PE), Polyvinyl Chloride	Packaging degrades in landfills	X-ray packaging material is a significant source of microplastics
17	Denture Polymers	Poly(methyl methacrylate) (PMMA)	Wear and degradation during use	Non-biodegradable; accumulates in landfills
18	Floss Containers	Polypropylene (PP), Polyethylene (PE)	Disposed of post-use fragments in landfills	Adds to single-use plastic burden
19	Plastic Caps and Seals for Dental Products	Polyethylene (PE), Polypropylene (PP)	Fragmentation after disposal	Plastic caps contaminate terrestrial and marine environments
20	Plastic Tubing and Handpieces	Polyvinyl Chloride (PVC)	Microplastics produced through abrasion during use	Frequently discarded, contributing to clinical waste microplastics

Table 2. Chitosan-based adsorbents for Dental Waste Microplastic Remediation highlight the range of chitosan derivatives and their mechanisms for microplastic remediation. These include nano-chitosan, chitosan-graphene oxide composites, and magnetic chitosan nanoparticles. The table also details their removal efficiencies, which can reach 96%, and observations regarding their functionality in real-world applications.

Table 2. Chitosan-Based Adsorbents for Dental Waste Microplastic Remediation

No.	Chitosan Derivative	Mechanism	Efficiency	Results	Observations
1	Chitosan	Electrostatic interactions with microplastic surfaces	85-90%	Effective removal efficiency in dental wastewater	Biodegradable, readily available, and low-cost material
2	Nano-Chitosan	High surface area increases the adsorption capacity	95%	High efficacy in laboratory settings for microplastic adsorption	Shows enhanced removal rates of smaller microplastic particles
3	Chitosan-Graphene Oxide Composite	Electrostatic and π-π interactions with microplastics	92%	Superior removal of dental wastewater contaminants	Enhanced stability and reusability in repeated cycles
4	Chitosan-Bentonite Hybrid	Adsorption via hydrogen bonding and ionic exchange	88%	Effective in removing larger microplastics	Bentonite enhances physical adsorption properties
5	Magnetic Chitosan Nanoparticles	Magnetic separation after adsorption	96%	Rapid removal of microplastics and easy recovery post-treatment	High recovery and minimal loss of adsorbent material
6	Chitosan Cross-linked with Glutaraldehyde	Improved structural stability for reuse	85%	Maintained removal efficiency in repeated cycles	High mechanical strength, low degradation rate
7	Chitosan-Carbon Nanotube Composite	Chemical adsorption via surface interactions	93%	Captures a wide range of microplastics in wastewater	Superior mechanical strength and stability
8	Chemically Modified Chitosan with Thiol Groups	Covalent bonding with microplastic contaminants	90%	High selectivity for negatively charged microplastics	Improved selectivity for charged pollutants
9	Chitosan with Polyvinyl Alcohol (PVA)	Adsorption through hydrogen bonding and electrostatic interactions	87%	Promising for large-scale wastewater systems	PVA addition enhances structural strength and water solubility
10	Nano-Chitosan Cross-linked with Silver Nanoparticles	Antibacterial and adsorptive properties for microplastics	94%	Reduces biofilm formation on dental microplastics	Dual function: microplastic removal and pathogen inactivation
11	Chitosan-ZnO Composite	Adsorptive and photocatalytic	89%	Effective in reducing microplastics and organic pollutants	Synergistic removal of organic and microplastic pollutants

		properties for microplastics			
12	Chitosan Hydrogel	Swelling and entrapment of microplastics in a gel matrix	80%	Effective for larger microplastic particles in dental wastewater	Swellable material ideal for continuous filtration
13	Chitosan-Coated Membranes	Filtration and adsorption combined mechanism	91%	Excellent for continuous flow systems in dental clinics	Suitable for scaling in dental wastewater management systems
14	Chitosan with Metal-Organic Frameworks (MOFs)	Combination of adsorption and molecular sieving	92%	Enhances selectivity and reusability in filtration applications	MOFs improve capacity for targeting microplastic contaminants
15	Chitosan-Gelatin Composite	Gel entrapment and electrostatic interactions	85%	The synergistic effect of gelatin improves mechanical properties	Good flexibility for application in dental waste management
16	Chitosan-Glyoxal Cross-linked Nanoparticles	Covalent binding with microplastics	88%	Efficient for larger volumes of dental wastewater	High binding efficiency even in lower concentrations of microplastics
17	Nano-chitosan with Activated Carbon	Adsorption via large surface area	90%	Effective for satisfactory particle capture in dental wastewater	Activated carbon enhances surface adsorption properties
18	Chitosan-Copper Nanocomposites	Combination of adsorption and antibacterial action	89%	Effective for dual removal of microplastics and microbial pathogens	Copper enhances antimicrobial properties
19	Chitosan-Cerium Oxide Nanoparticles	Adsorption through surface charge interactions	91%	Efficient in removing negatively charged microplastics	Highly selective for certain microplastic types
20	Chitosan-Silica Composite	Physical adsorption and trapping of microplastics	87%	Effective for larger particle sizes, especially in dental waste	Silica provides structural stability for extended use

III. Discussion

Integrating chitosan-based technologies in dental practices presents a transformative opportunity to address microplastic pollution. Chitosan's unique molecular structure and strong binding capacity for microplastics make it an ideal candidate for wastewater remediation. Its ability to interact with various polymers, such as polyethylene and polypropylene, positions it as a versatile and effective solution for mitigating environmental contamination in dental clinics (24). The development of advanced forms, such as nano-chitosan and hybrid composites, highlights the adaptability of chitosan to address varying levels of microplastic contamination.

In practice, adopting chitosan-enhanced filtration systems can significantly reduce the environmental footprint of dental clinics. For instance, filters using cross-linked or chemically modified chitosan exhibit improved selectivity and stability, enabling efficient removal of contaminants even under demanding operational conditions (26). The synergistic integration of chitosan with advanced technologies, including ultrafiltration membranes, biofilters, and graphene oxide composites, enhances its efficacy while maintaining environmental sustainability (28-30). However, widespread implementation faces several hurdles, including high production costs and scalability limitations. These issues are compounded by the absence of clear regulatory guidelines for integrating chitosan-based technologies into mainstream dental practices (31).

To overcome these challenges, a coordinated effort is required from stakeholders across the scientific, industrial, and governmental sectors. Establishing regulatory frameworks to mandate the use of biodegradable materials in dental waste management, coupled with financial incentives such as subsidies and tax rebates, can facilitate the adoption of chitosan-based solutions (32). Additionally, promoting research and development in cost-effective production methods for advanced chitosan materials can help address scalability concerns. The dental industry can transition toward a more sustainable future by aligning technological innovations with policy measures, reducing its contribution to global microplastic pollution.

Future Directions and Challenges

While chitosan-based technologies show considerable promise, their widespread adoption is hindered by challenges related to cost, scalability, and regulatory approvals. The production of advanced chitosan materials, such as nanoscale filters and smart composites, remains expensive, limiting their accessibility for smaller dental practices. Furthermore, regulatory frameworks must evolve to establish guidelines that mandate using environmentally friendly materials like chitosan while incentivizing sustainable practices through tax rebates or subsidies.

The integration of AI, Metaverse, AR, and VR can revolutionize the adoption of chitosan-based technologies by addressing key challenges like cost, scalability, and regulatory hurdles. AI can optimize material design and production processes, reducing costs by simulating nanoscale filters and smart composites, while predictive models identify scalable manufacturing methods. AR and VR can be leveraged for immersive training programs, demonstrating the benefits of chitosan-based materials to dental professionals and regulators, and enabling real-time visualization of their applications. The Metaverse can facilitate virtual marketplaces, connecting small dental practices with manufacturers and promoting cost-effective access to these materials. Additionally, AR and VR simulations can showcase environmental and economic impacts, helping policymakers establish supportive regulatory frameworks and incentivize sustainable practices through tax rebates or subsidies (33-36).

Policy and Financial Incentives

Comprehensive policies at both national and international levels are required to promote the adoption of chitosan-based remediation technologies. Financial incentives, such as grants for research and subsidies for implementation, can facilitate the transition to sustainable dental practices. Addressing cost and regulatory barriers can drive the development and widespread use of eco-friendly technologies in dentistry, paving the way for a more sustainable future.

IV. Conclusion

Microplastic pollution represents a significant environmental and health challenge, with dental practices contributing through plastic-based materials and improper waste management. Chitosan, a biodegradable, nontoxic, and highly adsorptive biopolymer, offers a promising solution for mitigating this issue. Its ability to effectively bind microplastics through electrostatic interactions and hydrogen bonding makes it versatile for wastewater treatment and pollution control. Advanced forms of chitosan, including nano-chitosan and hybrid composites, have demonstrated enhanced efficiency and adaptability in removing microplastics from dental wastewater.

Despite its potential, challenges such as production costs, scalability, and regulatory barriers hinder the widespread adoption of chitosan-based technologies. Addressing these challenges requires a multifaceted approach, including developing cost-effective production methods, establishing comprehensive regulatory frameworks, and providing financial incentives for sustainable practices. Integrating chitosan with advanced remediation technologies, such as biofilters, ultrafiltration membranes, and graphene oxide composites, further enhances its application potential and underscores its critical component in the transition toward sustainable dentistry.

The dental industry can significantly reduce its contribution to global microplastic pollution by prioritizing innovation, regulatory alignment, and financial support. Chitosan-based technologies effectively address environmental concerns and represent a step toward more sustainable and eco-friendly healthcare practices. Adopting these solutions holds the promise of safeguarding ecosystems, reducing health risks, and fostering a greener future for dentistry.

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