Sustainable Orthodontics: From Environmental Footprint to Eco-Conscious Clinical Practice

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Abstract

Growing global concern regarding environmental sustainability has prompted healthcare professionals to critically assess the ecological impact of clinical practices in dentistry and more recently, orthodontics as well. Subsequently, the concept of sustainable orthodontics has emerged, emphasizing clinical practices that minimize environmental harm while maintaining patient safety and treatment effectiveness. This review highlights the principles of sustainable orthodontics including sustainable materials, digital technology, energy-efficient clinical practices, waste-management strategies as well as the challenges associated with their implementation in orthodontic practice.

Keywords: sustainable orthodontics; environmental sustainability; green orthodontics; eco-conscious orthodontics.

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Introduction

Dentistry, including orthodontics, contributes substantially to the environmental impact through its reliance on disposable materials, energy-intensive equipment and sterilization processes.[1,2] Many of these materials are non-biodegradable and when inadequately managed, contribute to long-term environmental pollution and increased biomedical waste generation.[3] Furthermore, exposure of orthodontic materials to the oral environment including variations in temperature, pH and salivary composition can accelerate material degradation and contamination.[3] This limits opportunities for reuse or recycling and further increases the volume of clinical waste requiring disposal.[4,5] In response to these challenges, the concept of sustainable orthodontics has evolved, emphasizing efficient resource utilization, waste reduction, recycling and environmentally responsible clinical decision-making.[6] Sustainable orthodontics applies these principles specifically to orthodontic practice, promoting strategies that minimize environmental impact while maintaining patient safety, treatment effectiveness and ethical standards of care.[7] The concept of green orthodontics, eco-friendly orthodontics and sustainable orthodontics share a common objective of reducing the environmental impact of orthodontic care through responsible resource utilization, waste reduction and environmentally conscious clinical practices.[5,7]

While conventional orthodontic practice generates substantial quantities of wastes creating significant challenges in waste segregation and safe disposal, recent advancements in digital orthodontics offer opportunities to reduce material waste, improve workflow efficiency and support more sustainable clinical practices.[8,9,10,11] Despite growing awareness of environmental sustainability, the widespread implementation of eco-friendly orthodontic practices remains limited. Hence, a comprehensive understanding of sustainable materials, energy-efficient clinical practices, digital technologies, waste-management strategies and implementation challenges is needed to facilitate the transition towards environmentally responsible orthodontic care. Therefore, this review aims to provide a comprehensive overview of current concepts, technologies, materials and clinical strategies related to sustainable orthodontics and to discuss the opportunities and challenges associated with their implementation.

Environmental Impact of Orthodontic Practice

In general, orthodontic practice contributes to environmental burden due to prolonged treatment duration, frequent clinical visits and the continuous use of disposable materials.[12] Moreover, orthodontic therapy often spans several months to years, resulting in repeated consumption of auxiliaries and consumables and creating a cumulative ecological burden over time.[12] A substantial proportion of orthodontic materials including plastic brackets, elastomeric modules, impression trays and packaging materials are derived from petroleum-based polymers.[13] Clear aligners, retainers and various orthodontic appliances are commonly fabricated from thermoplastic materials such as polyethylene terephthalate glycol (PETG) and polyurethane, which are non-biodegradable and significantly contribute to the generation of plastic wastes.[14,15] Elastomeric components, routinely replaced at each appointment, generate considerable waste and are generally managed as clinical waste because of contamination concerns after intraoral use limiting their potential for recycling.[16,17] However, these materials persist in the environment following disposal contributing to long-term plastic pollution. In addition to material waste, energy consumption represents a major environmental concern in orthodontic practice.[7] Continuous electricity use for lighting, sterilization and treatment planning systems contribute to increased carbon emissions.[17] Sterilization procedures are particularly energy-intensive and may involve chemical agents that require careful handling and disposal to minimize environmental harm.[18,19] Water consumption also contributes to the environmental footprint of orthodontic offices. Substantial amounts of water are consumed during instrument cleaning, sterilization cycles and routine clinic maintenance, while inefficient water-management systems can lead to unnecessary wastage.[20] Additive manufacturing processes generate waste in the form of failed prints, support structures, excess resin and contaminated cleaning solutions.[21] Furthermore, ultraviolet curing units, thermoforming machines, scanners and 3D printers require significant energy consumption, thereby increasing the carbon footprint of orthodontic treatment. The production of thermoplastic materials used in these technologies also contributes to greenhouse gas emissions through raw material extraction, polymer manufacturing and industrial processing.[22] Inadequate waste-management practices can lead to environmental contamination and potential public health risks.[23] Collectively, these factors highlight the substantial environmental burden associated with orthodontic care and underscore the need for sustainable materials, resource-efficient technologies and environmentally responsible clinical practices.

Sustainable Materials in Orthodontics

Material selection is a key determinant of the environmental impact of orthodontic practice.[7] Conventional orthodontic materials are largely composed of metals and petroleum-based polymers that require energy intensive manufacturing and present challenges in recycling, contributing to long-term environmental pollution. Sustainable orthodontics frameworks emphasize that responsible material selection is essential to reduce environmental burden without compromising clinical performance.[11,12] Orthodontic brackets and wires are commonly fabricated from stainless steel, nickel-titanium alloys and ceramics. Although metallic components are potentially recyclable, contamination after clinical use and limited recycling infrastructure restrict effective recovery in routine practice. Improving material segregation and recycling pathways during appliance replacement and debonding have been identified as a practical approach to reduce waste generation.[24,25] Sustainable orthodontics also involves reducing energy consumption through the use of energy-efficient equipment, light emitting diode (LED) curing systems and environmentally responsible clinical protocols.[10] Adhesives and bonding agents may contain chemical components that pose environmental risks if improperly disposed. The development of materials with reduced toxic content aligns with the principles of sustainable orthodontic practice. [12] Clear aligner therapy (CAT) presents additional sustainability concerns, as treatment requires multiple sets of single-use thermoplastic aligners resulting in increased plastic waste. Their fabrication involves thermoforming processes that require substantial thermal energy to heat and mould plastic sheets, contributing further to energy consumption during production. Although bio-based plastics have emerged as potential alternatives, their sustainability depends on material composition, manufacturing efficiency and end-of-life recyclability.

Sustainable Clinical Practices and Resource Conservation

Routine clinical practices should be optimized to reduce unnecessary resource consumption and waste generation as these contribute to the environmental footprint of orthodontic care. Even small modifications in daily clinical operations can support long-term sustainability and thereby reduce the environmental burden. Regular equipment maintenance and efficient scheduling of high-energy devices help to minimize unnecessary energy usage and improve overall resource efficiency. Large volumes of water are used during instrument cleaning, sterilization cycles and routine clinic maintenance. Installing water efficient fixtures, preventing water leaks through regular plumbing maintenance and optimizing sterilization protocols can substantially decrease water consumption.[32] Digital workflows may contribute to water conservation by minimizing the need for gypsum model fabrication and impression material processing. Alongside energy and water conservation, environmentally responsible infection control practices are essential for sustainable clinical care. Although sterilization and disinfection procedures are indispensable for maintaining patient safety, they may pose environmental challenges due to high energy requirement and chemical disposal. Steam sterilization is generally considered more environmentally favourable than chemical-based methods when properly managed.[32] Furthermore, the use of environmentally safer disinfectants and adherence to proper disposal guidelines can help in reducing environmental contamination and occupational exposure. Paper reduction strategies also contribute to sustainable orthodontic practice. Administrative practices also offer opportunities to enhance sustainability. Transitioning appointment scheduling, billing, consent forms and patient education materials to electronic platforms significantly lessen the resource consumption while improving operational efficiency.[2,7] Such digital solutions not only reduce waste generation but also streamline practice management.

Digital Orthodontics and Environmental Sustainability

The integration of digital technology into orthodontic practice has contributed significantly to environmental sustainability.[19] Digital orthodontics reduces reliance on conventional consumable materials, minimizes waste generation and improves workflow efficiency, thereby lowering the overall ecological footprint of orthodontic care.[26] The transition from conventional to digital systems represents a shift towards more environmentally responsible orthodontic practice. One of the most impactful advancements is the adoption of digital impressions as an alternative to conventional elastomeric impression materials and dental stone models. Traditional impression techniques are associated with material wastage, frequent retakes and disposal challenges, whereas intraoral scanning eliminates the need for impression materials and gypsum models.[27] Computer-aided design and computer-aided manufacturing (CAD/CAM) technologies further enhance sustainability by optimizing material usage during appliance fabrication.[28] Digitally planned appliances allow precise customization and production, reduce material wastage and improve manufacturing efficiency.[29] In addition, digital workflows reduce the physical transportation of impressions and models between clinics and laboratories, thereby lowering transportation-related carbon emissions. Three-dimensional (3D) printing is increasingly used for the fabrication of study models, aligners, retainers and auxiliary appliances. Although resin waste remains a concern, additive manufacturing generally requires less material than conventional subtractive techniques.[30] The development of recyclable and bio-based printing resins has been identified as an important step towards improving the environmental sustainability of orthodontic 3D printing.[30] Tele-orthodontics and remote monitoring technologies provide additional environmental benefits by reducing the need for frequent in-office visits thereby reducing travel-related carbon emissions.[31] Despite these advantages, the environmental impact of digital orthodontics is influenced by energy consumption and electronic waste generation. Sustainable implementation therefore requires the use of energy-efficient equipment and appropriate management and recycling of electronic wastes in accordance with established guidelines. When implemented responsibly, digital orthodontics represents an effective strategy for reducing the environmental burden of orthodontic practice while maintaining clinical precision and quality of care.

Waste Management and Recycling in Orthodontics

Effective waste management is a fundamental component of sustainable orthodontic practice, as orthodontic clinics generate a wide range of waste

including biomedical waste, plastics, metals, paper and electronic waste. Inadequate handling and disposal of these materials can result in environmental pollution and public health risks, highlighting the need for structured and standardized waste management protocols. Orthodontic wastes are broadly classified into infectious biomedical wastes and non-infectious general wastes.[33] Proper segregation at the point of generation is essential to ensure safe disposal and facilitate the recycling of materials. The use of color-coded disposal systems, along with regular staff training, helps to reduce cross-contamination and limits the volume of wastes requiring specialized treatment. Plastic wastes represent a major sustainability challenge in orthodontics due to the extensive use of elastomeric components, aligners, packaging materials and single-use consumables. Most orthodontic plastics are non-biodegradable and difficult to recycle because of their material composition and contamination during clinical use. Reducing unnecessary plastic consumption and exploring recyclable or biodegradable alternatives may help mitigate this environmental impact. In addition to plastic wastes, orthodontic offices generate substantial quantities of metal wastes including archwires, brackets and bands. Many of these materials particularly stainless steel and nickel titanium alloys possess considerable recycling potential when appropriately segregated.[34] Besides this, life-cycle assessment (LCA) studies have highlighted the increasing environmental burden associated with plastic intensive orthodontic therapies, particularly clear aligner therapy (CAT).[35] Establishing systematic collection protocols and collaborating with certified recycling facilities can substantially improve metal recycling outcomes and reduce the demand for raw materials. Adopting a circular economy approach that prioritizes waste reduction, safe reuse where appropriate and recycling can substantially enhance sustainability in orthodontic practice. Through effective waste segregation, recycling initiatives and collaboration with environmentally responsible suppliers, orthodontic offices can reduce landfill burden and contribute to environmentally sustainable healthcare delivery.

Role of Manufacturers and the Orthodontic Industry

Manufacturers and the orthodontic industry play a critical role in promoting sustainable orthodontic practices through their influence on material development, packaging, production processes and professional education. Since manufacturing, packaging and distribution of orthodontic products contribute substantially to the overall environmental footprint of orthodontic care, industry-driven sustainability initiatives are essential for reducing this impact.[7] The development of recyclable metallic components, biodegradable polymers and environmentally safer elastomeric materials has gained increasing attention.[7] Advances in material sciences have enabled the production of orthodontic appliances with reduced environmental persistence while maintaining mechanical performance and biocompatibility. Furthermore, life cycle assessment (LCA) approaches allow manufacturers to evaluate environmental impact across all stages of product life, supporting evidence-based improvements in sustainability.[35] Packaging practices also offer opportunities for waste reduction. Excessive plastic and multilayer packaging contribute significantly to environmental burden. The adoption of minimal, recyclable or biodegradable packaging, along with bulk supply and refillable systems can substantially reduce waste generation in orthodontic offices. In addition to this, energy-efficient manufacturing processes and responsible sourcing of raw materials also enhance environmental sustainability by reducing the greenhouse gas emissions associated with production and transportation. Transparency in environmental reporting and compliance with recognized sustainability standards further strengthen the accountability within the orthodontic industry. Manufacturers can further support sustainable orthodontics through product recycling programs, particularly for clear aligners, impression trays and plastic packaging. Such initiatives promote responsible disposal and reinforce circular economy principles.[7] Beyond product development, industry-led research and educational programs can increase awareness among clinicians and encourage the adoption of sustainable orthodontic practices. Through innovation, responsible manufacturing and collaboration with clinicians, the orthodontic industry can significantly advance environmentally sustainable orthodontic care.

Role of the Orthodontic Team and Patient Awareness

The successful implementation of sustainable orthodontics depends on the active involvement of the orthodontic team and informed patients.

Awareness and behavioural changes are essential for translating sustainability principles into routine clinical practice. The orthodontic team including orthodontists, assistants, hygienists and administrative staff plays a central role in adopting sustainable practices. Training programs improve understanding of the environmental impact of routine procedures and promote responsible behaviours such as waste segregation, efficient resource utilization, recycling and paperless documentation.[7] Chairside assistants help to reduce material wastage and ensure proper biomedical waste handling, while administrative staff support sustainability through digital scheduling, billing and electronic record keeping systems. Patient awareness is equally important in supporting sustainable orthodontic practices. Educating patients about eco-friendly approaches, including digital workflows, reduced paper use and responsible appliance disposal, encourages cooperation and environmentally responsible behaviour. Increased patient awareness also strengthens trust and aligns orthodontic care with the growing demand for sustainable healthcare services.

Challenges and Limitations of Sustainable Orthodontics

Despite increasing awareness of environmental sustainability in healthcare, the widespread adoption of sustainable orthodontic practices remains limited due to several challenges. One of the major barriers is the initial financial investment required for digital technologies, energy-efficient infrastructure and sustainable materials.[36,37,38] Such investments may pose substantial financial challenges for smaller practices, particularly in resource-constrained settings. Beyond financial constraints, the limited availability of clinically validated sustainable orthodontic materials further restricts implementation. Although research on biodegradable and recyclable alternatives is expanding, many products lack long-term clinical evidence regarding durability, performance and cost-effectiveness.[7] This uncertainty contributes to practitioner hesitation and slow adoption of sustainable innovations. Another important limitation is the absence of standardized sustainability guidelines specific to orthodontics. As a result, sustainable practices vary widely across clinical settings, limiting consistent implementation and evaluation.[7]

Future Perspectives and Research Directions

The future of sustainable orthodontics depends on continued innovation and evidence-based implementation. Advances in material sciences are expected to support the development of biodegradable polymers, recyclable aligner systems and low-impact elastomeric materials without compromising clinical performance.[10] Long-term clinical studies are necessary to establish the safety, durability and effectiveness of these sustainable alternatives. Life-cycle assessment (LCA) studies will remain essential for evaluating the overall environmental impact of orthodontic materials and treatment modalities. Such assessments provide objective data that can guide clinicians and manufacturers towards environmentally responsible decision- making. Emerging technologies, including artificial intelligence-driven treatment planning and expanded tele-orthodontic models, may further optimize resource use, reduce unnecessary clinical visits and lower travel-related carbon emissions.[39,40] Future research should also focus on randomized controlled clinical trials and standardized outcome measures to strengthen the evidence base for sustainable orthodontic approaches. Integrating sustainability concepts into orthodontic education and professional guidelines is critical for long-term adoption. Collaboration among clinicians, manufacturers, policymakers and professional organizations will be essential to establish standardized sustainability frameworks and promote environmentally responsible orthodontic care globally.

Conclusion

Sustainable orthodontics represents an essential transition in contemporary orthodontic practice, addressing the growing environmental burden associated with conventional care. It has the potential to improve clinical efficiency while reducing the environmental burden. However, more evidence is required to evaluate the long-term effectiveness and sustainability. Moreover, the successful implementation of sustainable clinical practices requires commitment at both individual and organizational levels. By integrating energy-efficient infrastructure, resource conservation strategies, environmentally responsible sterilization protocols and digital technologies in to routine practice, orthodontic offices can limit their ecological footprint while maintaining high standards of patient care and infection control.

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