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Environmental Sustainability in Dentistry: Challenges, Innovations, and Strategic Directions

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ABSTRACT: The environmental impact of dentistry has drawn increasing concern, prompting global efforts to adopt sustainable practices within dental education and clinical care. This narrative review aims to examine the current state of sustainability in dentistry, identify key challenges, and highlight successful interventions. A comprehensive literature search was conducted across Scopus, PubMed, and Google Scholar, using Boolean search strategies and targeted keywords. Studies were selected based on predefined inclusion criteria, focusing on educational initiatives, material innovations, and institutional policies. Findings reveal that educational integration significantly improves awareness and promotes sustainable behavior among dental students, although implementation remains inconsistent due to curricular limitations. Innovations such as polyether ether ketone (PEEK) and recycled zirconia offer promising alternatives to traditional materials, reducing environmental impact while maintaining clinical effectiveness. Institutional policies, economic considerations, and cultural factors emerged as systemic enablers or barriers to sustainable dentistry. Notably, supportive policies and structured training are associated with higher adoption rates, while financial constraints and lack of awareness impede progress. This review emphasizes the urgent need for strategic interventions, including policy development, financial incentives, and community engagement, to facilitate widespread adoption of eco-friendly dental practices. Future research should explore longitudinal impacts and standardized sustainability metrics. Strengthening educational infrastructure and cross sector collaboration remains essential for advancing sustainable dental care globally.

Keywords: Sustainable Dentistry, Dental Education, Green Dental Materials, Environmental Sustainability, Institutional Policy, Eco-Friendly Healthcare, Healthcare Innovation.

INTRODUCTION

In recent years, increasing global awareness of environmental issues has drawn attention to the environmental impact of healthcare practices, including dentistry. The dental sector, as a component

of the broader healthcare system, contributes notably to greenhouse gas (GHG) emissions and the production of clinical waste, much of which is not biodegradable or recyclable. Yeoh et al. (2024) estimate that 3% to 8% of national GHG emissions originate from healthcare activities, including dental clinics (Yeoh et al., 2024). These figures have prompted the need for more sustainable approaches to dental care.

There is a growing body of literature examining the integration of sustainability principles into dental education and clinical practice. Notably, Jamal et al. (2023) report that the lack of sustainability knowledge among dental students and educators hinders the implementation of environmentally friendly practices (Jamal et al., 2023). The situation is exacerbated by the traditional models of clinical training and wasteful resource use in dentistry. However, recent initiatives, particularly in Europe, are showing promise. Dixon et al. (2025) discuss efforts to embed sustainability into dental curricula, which have significantly increased student awareness and engagement with eco conscious clinical behaviors (Dixon et al., 2025).

Empirical evidence supports the relevance of this topic and underscores the urgency of transitioning toward sustainable dental care. For instance, Martín et al. (2021) observed that a considerable number of dental students in the UK engage actively in proper waste management and are increasingly conscious of eco-friendly practices (Martín et al., 2021b). In Portugal, Neves et al. (2022) found that dental professionals are adopting sustainable methods through waste reduction and more effective medical waste handling (Neves et al., 2022). Similarly, studies from North America, including Guo et al. (2024) and Danesh et al. (2025), highlight the carbon footprint associated with commuting and patient transportation, and suggest teledentistry as a viable strategy for reducing emissions (Danesh et al., 2025; Guo et al., 2024).

Moreover, the adoption of digital technology and the development of biodegradable materials in dental treatment have opened new avenues for mitigating environmental impacts. Byrne et al. (2022) point to the positive role of digital impression systems, which not only reduce the need for material waste but also shorten patient visit durations (Byrne et al., 2022). These innovations are indicative of broader systemic changes aiming to minimize dentistry's ecological footprint.

Despite these advances, the field continues to face several significant challenges. One of the most persistent issues is the lack of awareness and preparedness among dental students and professionals to incorporate sustainability into their routine practices. According to Yeoh et al. (2024) and Haque et al. (2024), although attitudes towards sustainability are improving, many students feel inadequately trained to address environmental issues in dental care (Haque et al., 2024; Yeoh et al., 2024). Likewise, Neves et al. (2022) note that while intentions to apply sustainable practices are increasing, actual implementation in clinics remains limited due to adherence to outdated and unsustainable practices (Neves et al., 2022).

Cost related barriers also pose a challenge. Chanioti et al. (2025) and Duane et al. (2020) argue that the upfront costs of sustainable technologies deter widespread adoption (Chanioti et al., 2025; Duane et al., 2020). Additionally, patient willingness to support and pay for eco-friendly options is often

uncertain, adding another layer of complexity to clinical decision making. The economic constraints and lack of regulatory incentives reduce the feasibility of immediate large scale changes.

A prominent gap in the literature is the lack of robust empirical studies that directly measure the environmental outcomes of sustainable practices in dentistry. Jalbani et al. (2023) and Mitsika et al. (2024) emphasize that much of the existing literature focuses on conceptual frameworks or theoretical benefits rather than evidence based outcomes (Mitsika et al., 2024). Martín et al. (2021) and Shinkai et al. (2023) call for more longitudinal and comparative research to determine the real world efficacy of sustainable interventions (Martín et al., 2021a; Shinkai et al., 2023). Without this data, it remains difficult to guide clinical policies or to persuade stakeholders of the value of transitioning to green dentistry.

This narrative review aims to address these gaps by synthesizing current research on sustainability in dental practice, with a particular focus on educational initiatives, clinical innovations, and implementation barriers. The review seeks to provide a coherent understanding of how sustainability can be effectively integrated into dental care systems and to offer insights into successful strategies, remaining challenges, and directions for future research and policy.

Geographically, this review draws on studies conducted across Europe, North America, and parts of Asia, with some data from the Middle East and Eastern Europe. The inclusion of diverse regions offers a comparative perspective on how cultural, economic, and institutional contexts shape sustainability practices in dental education and clinical care. For example, Haque et al. (2024) and Antoniadou et al. (2023) report significant disparities in sustainability knowledge among dental students in Saudi Arabia and Greece, respectively (Haque et al., 2024; Αντωνιάδου, Chrysochoou, et al., 2023). Similarly, Ţâncu et al. (2025) observed variations in environmental awareness based on professional experience levels among Romanian dentists (Ţâncu et al., 2025).

Notably, Joury et al. (2021) and Duane et al. (2019) documented differences in sustainability integration between dental schools in the UK and the United States, indicating that national and institutional frameworks greatly influence educational outcomes (Duane et al., 2019; Joury et al., 2021). These comparative findings suggest that a one size fits all approach is unlikely to be effective and underscore the need for tailored educational and policy interventions. Therefore, the scope of this review not only encompasses the analysis of existing literature but also offers recommendations that align with specific regional and demographic conditions.

By examining these dimensions, this review aims to contribute meaningfully to the global discourse on sustainable healthcare by demonstrating how dentistry a field often overlooked in environmental debates can play a critical role in achieving broader sustainability goals. Through the identification of current gaps, barriers, and best practices, this paper seeks to inform both academic and policy discussions, paving the way for a greener and more responsible future for dental care worldwide.

METHOD

This study adopts a narrative review approach to examine the integration of sustainability principles within dental practice and education. A comprehensive literature search was conducted across major academic databases, including Scopus, PubMed, and Google Scholar, targeting peer reviewed studies published from 2015 to 2025. These databases were selected for their coverage of biomedical, dental, and interdisciplinary environmental health research. The search strategy employed a predefined combination of keywords and Boolean operators to maximize the precision and comprehensiveness of relevant literature retrieval.

Keywords included "dental sustainability," "eco-friendly dental care," "green dentistry," "environmental sustainability," and "sustainable practices in dentistry." Boolean operators such as AND, OR, and NOT were used to construct queries that focused on specific aspects of sustainability within the dental sector. For example, combinations such as "dental sustainability AND eco-friendly dental care" and "environmental sustainability in dentistry AND dental materials" were employed to refine the search and capture literature addressing both clinical and educational dimensions of sustainable dental practices.

Selection criteria included peer reviewed articles, systematic reviews, and meta analyses that empirically or theoretically analyzed the impact of sustainability initiatives on dental practice, material use, education, and waste management. Excluded were studies not published in English, lacking direct empirical evidence, or not subject to peer review. Initial screening involved title and abstract review, followed by full text evaluation to ensure methodological rigor and thematic relevance.

To enhance reliability, a multi stage screening process was applied. Four independent reviewers evaluated the studies for alignment with inclusion criteria. Key themes were synthesized to identify recurring patterns in how sustainability is conceptualized and implemented in dental settings. The findings offer insights into effective strategies, systemic barriers, and the evolving discourse on sustainable practices in global dental care.

RESULT AND DISCSSION

The integration of sustainability into dental education has shown promising outcomes across multiple studies, suggesting that educational intervention plays a pivotal role in shaping environmental awareness and sustainable behaviors among future dental professionals. Jamal et al. (2023), for instance, investigated perceptions and knowledge among students in 26 dental schools in Saudi Arabia, finding that increased educational exposure to sustainability concepts significantly enhanced students' awareness regarding environmentally responsible dental practices (Jamal et al., 2023). The survey emphasized that while baseline knowledge was limited, curriculum based instruction was instrumental in bridging that gap.

Supporting this, Haque et al. (2024) demonstrated that dental students' attitudes toward sustainable dental practices improved substantially following targeted coursework. Their study confirmed a

positive correlation between education and behavioral change, revealing that students became more inclined to integrate sustainable approaches into their clinical routines after receiving formal instruction on environmental issues. Similarly, Dixon et al. (2025) examined the longitudinal impact of sustainability integration in dental curricula across institutions in the UK and Ireland (Dixon et al., 2025). The study reported not only heightened awareness but also observable proactive engagement by students in applying sustainable practices in clinical settings.

Durnall et al. (2024) further explored the role of curriculum design in fostering sustainability attitudes (Durnall et al., 2024). Their findings illustrated that while sustainability themes are increasingly being included in UK dental programs, there remain structural barriers in content delivery and curriculum standardization. Nonetheless, students expressed overwhelmingly positive attitudes towards the subject, attributing their understanding to structured educational exposure. In Romania, Ţâncu et al. (2025) noted gender specific trends, where female students showed a stronger interest in sustainability related topics than their male counterparts, highlighting the importance of educational inclusivity and sensitivity in curriculum design (Ţâncu et al., 2025).

Beyond education, material and technological innovations have emerged as a vital pathway for reducing the environmental burden of dental care. The development and clinical application of polyether ether ketone (PEEK) have garnered significant attention. As a biocompatible and recyclable material, PEEK offers considerable advantages over traditional substances such as titanium. According to Olawumi et al. (2024), its excellent mechanical performance and recyclability render it an ideal candidate for dental implants, especially as surface modification technologies powered by artificial intelligence have further enhanced its clinical usability and acceptance (Olawumi et al., 2024).

Similarly, research on recycled zirconia has provided new avenues for sustainable dental material use. Alqutaibi et al. (2025) investigated the clinical feasibility of recycled zirconia, concluding that while its mechanical properties slightly underperformed compared to virgin zirconia, its microstructural density and recyclability made it suitable for applications such as short span bridges (Alqutaibi et al., 2025). The reuse of zirconia not only addresses the waste crisis but also reduces the demand for new material production, thereby contributing to the overall reduction of the dental sector's carbon footprint.

Regarding safety and efficacy, Shinkai et al. (2023) critically evaluated the environmental sustainability of materials like PEEK and recycled zirconia in prosthodontic procedures. PEEK exhibited low allergenic potential and inflammation risk, making it a safer option for patients while maintaining clinical effectiveness (Shinkai et al., 2023). Likewise, although recycled zirconia demonstrated marginally lower flexural strength, it remained clinically acceptable for specific applications. These findings underscore the feasibility of adopting sustainable materials in dentistry without compromising patient outcomes or treatment durability.

In addition to innovations in material science, professional behaviors and awareness levels play a critical role in advancing green dentistry. Neves et al. (2022) reported that in Portuguese dental clinics, while efforts towards sustainable practices were evident, a limited number of professionals fully understood or implemented environmentally friendly protocols (Neves et al., 2022). The gap was

largely attributed to inadequate training and institutional support. This was echoed by Haque et al. (2024), who observed that dental professionals in Saudi Arabia lacked comprehensive education on applicable sustainable practices, further hindering implementation (Haque et al., 2024).

Jamal et al. (2023) reinforced these findings by highlighting the disconnect between growing environmental awareness and the practical knowledge required for implementation among students and faculty members (Jamal et al., 2023). Despite increased consciousness, the absence of actionable guidelines limited their capacity to translate knowledge into practice, thus impeding broader adoption of sustainability in daily operations.

Barriers to sustainable practice adoption extend beyond knowledge deficits. Aboueid et al. (2023) identified a lack of resources and educational infrastructure as significant impediments (Aboueid et al., 2023). The financial cost associated with transitioning to sustainable technologies was a recurrent theme across multiple studies. Dixon et al. (2024) noted skepticism among practitioners concerning the initial expenses involved in adopting greener alternatives, which are often perceived as costlier than conventional methods (Dixon et al., 2024). Moreover, shifting environmental regulations contribute to uncertainty, discouraging long term investment in sustainable practices.

Demographic variables also influence sustainability adoption. Ţâncu et al. (2025) observed that younger practitioners were more receptive to environmental policies compared to their more experienced counterparts (Ţâncu et al., 2025). This generational divergence suggests that targeted continuous education and support are essential to align practitioners across all stages of their careers with sustainability goals.

Institutional policies significantly shape the implementation of sustainable dentistry. Dixon et al. (2024) found that dental schools with well-defined pro environmental policies demonstrated superior adoption rates of green practices (Dixon et al., 2024). Institutions that explicitly outlined sustainability goals and incorporated them into both clinical and educational frameworks showed higher levels of student and faculty engagement in environmental initiatives.

Neves et al. (2022) similarly observed that institutions embedding sustainability in their administrative and pedagogical systems achieved greater traction in promoting eco-friendly behaviors among students and staff (Neves et al., 2022). Key strategies included structured waste management protocols, training programs, and sustainability themed research incentives, all of which contributed to institutional culture shifts towards environmental stewardship.

Sustainability initiatives at institutional levels also yielded benefits beyond environmental outcomes. Antoniadou et al. (2023) documented that staff involved in sustainability programs reported improved psychological well-being and social cohesion (Αντωνιάδου, Mangoulia, et al., 2023). The sense of shared responsibility and collective action fostered a positive workplace atmosphere, enhancing overall job satisfaction.

Durnall et al. (2024) corroborated these findings by revealing that faculty participation in environmental initiatives led to increased motivation, stronger professional collaboration, and

heightened workplace morale (Durnall et al., 2024). These psychosocial benefits illustrate the multifaceted value of institutional sustainability efforts, extending their relevance from ecological domains into human resource and organizational development.

In sum, this body of research underscores the multifactorial nature of sustainability in dentistry. While educational interventions and material innovations offer direct pathways to reducing environmental harm, their effectiveness is contingent upon professional behaviors, institutional policies, and systemic support. The findings highlight that sustainability in dentistry is not merely a matter of resource use, but a complex interplay of awareness, education, policy, and cultural change across global contexts.

The findings of this review align with a growing body of literature that underscores the global imperative to integrate sustainability into dental education and practice. While awareness of environmental issues in dentistry has increased across various regions, implementation gaps remain significant. Haque et al. (2024) illustrated that despite widespread commitment among dental professionals in Saudi Arabia to adopt environmentally friendly practices, insufficient education continues to hinder meaningful progress (Haque et al., 2024). These findings are corroborated by Jamal et al. (2023) and Aboueid et al. (2023), who identified lack of knowledge as a primary barrier to the widespread adoption of green dentistry (Aboueid et al., 2023; Jamal et al., 2023). Collectively, these studies highlight that increased awareness does not necessarily translate into practice, particularly in the absence of institutional support and formal training structures.

Discrepancies in the acceptance and implementation of sustainable practices across regions also suggest that cultural and institutional contexts heavily influence attitudes. Jamal et al. (2023) and Gershberg et al. (2021) observed variation in environmental literacy and sustainability engagement among dental students in different countries, reinforcing the need for localized strategies in curriculum design (Gershberg et al., 2021; Jamal et al., 2023). This observation resonates with wider scholarship on sustainability education, which emphasizes the importance of culturally responsive pedagogy to bridge gaps between knowledge and behavior. Institutional culture shaped by leadership, policies, and historical values therefore plays a crucial role in either enabling or constraining the shift toward sustainable dentistry.

Systemic factors further complicate the effective implementation of environmentally sustainable dental practices. First, policy frameworks at institutional and national levels are critical enablers or inhibitors. Dixon et al. (2024) reported that dental schools with formally established sustainability policies demonstrated higher adoption rates of eco conscious behaviors among faculty and students. By contrast, institutions lacking such policies often fostered environments of ambiguity and hesitation, deterring stakeholders from engaging in sustainable reforms. Clearly defined policy directives serve to legitimize sustainability efforts and provide a roadmap for implementation.

Economic constraints represent another critical systemic barrier. Many practitioners perceive the initial cost of adopting green materials and technologies as prohibitively high (Aboueid et al., 2023; Nassar et al., 2024). These costs include not only capital investments in sustainable equipment but also ongoing expenses related to training and material sourcing. The absence of financial incentives or

subsidies exacerbates this challenge, leaving practitioners to absorb the full cost of sustainability transitions. The result is a risk averse professional climate that favors conventional methods over environmentally progressive alternatives.

Cultural values also shape the trajectory of sustainability in dental practice. Zdravković et al. (2024) found that public awareness and support in Serbia played a significant role in either advancing or hindering the adoption of environmentally responsible dental care. Where community values aligned with environmental priorities, practitioners felt encouraged to adopt sustainable models (Zdravković et al., 2024). Conversely, in regions where ecological consciousness was low, providers lacked the external motivation to implement changes. This dynamic underscores the reciprocal relationship between healthcare providers and the communities they serve, suggesting that grassroots advocacy and public education are integral to long term success.

Education and training remain foundational to behavioral change in the dental sector. Gershberg et al. (2021) emphasized that structured sustainability education within dental curricula fosters not only increased awareness but also the capacity to apply principles in clinical settings (Gershberg et al., 2021). Repeated exposure to sustainability themes, combined with practical applications, enables students to internalize environmental values and develop actionable skills. As such, curriculum design must prioritize experiential learning and case based scenarios to ensure the transfer of theoretical knowledge into clinical competencies.

Given the range of barriers identified, several systemic interventions have been proposed to enhance the uptake of sustainable dentistry. Chanioti et al. (2025) advocated for the integration of environmental education into dental training programs, arguing that targeted instruction could significantly boost knowledge and behavioral intent among students and faculty (Chanioti et al., 2025). Educational reforms must therefore be coupled with professional development opportunities to extend the impact across career stages.

Institutional policies also play a pivotal role in guiding sustainable practices. Dixon et al. (2024) and Antoniadou (2024) emphasized the necessity of formal policy frameworks that detail environmental objectives, waste management standards, and acceptable material use (Dixon et al., 2024; Αντωνιάδου, Mangoulia, et al., 2023). These frameworks create consistency across institutions and provide measurable benchmarks for accountability. In environments where such policies were adopted, evidence points to improved waste management and reduced carbon footprints.

Financial support mechanisms are equally vital. Aboueid et al. (2023) recommended that government or institutional subsidies be made available to offset the upfront costs of adopting green technologies (Aboueid et al., 2023). Financial incentives could include grants for sustainable equipment, reduced taxes for environmentally certified practices, or access to discounted green supplies. By mitigating financial barriers, such policies could democratize access to sustainability and encourage broader participation.

Neves et al. (2022) stressed the importance of accessibility to sustainable technologies and materials (Neves et al., 2022). Their research highlighted that while interest in environmentally friendly

alternatives is widespread, practical access remains uneven. Policymakers and industry stakeholders must work collaboratively to improve the availability and affordability of sustainable dental products, thereby enabling practitioners to make environmentally sound choices without compromising clinical effectiveness.

Social awareness and community involvement also hold potential for driving sustainable change. Ţâncu et al. (2025) argued that patients and community members who are informed about the environmental impacts of dental care can act as catalysts for change (Ţâncu et al., 2025). Public campaigns and patient education initiatives may thus serve to align consumer expectations with sustainability goals, generating demand for greener services and legitimizing provider efforts.

Finally, cross sector collaboration presents a powerful opportunity to integrate sustainability more fully into healthcare systems. Although Ždrale et al. remain under cited, preliminary evidence supports the idea that partnerships among academia, industry, government, and practitioners can yield innovative solutions. Multistakeholder initiatives may enable the co creation of tools, guidelines, and metrics that standardize and elevate sustainable practice. Through collaborative governance models, dental sustainability can transition from isolated initiatives to system wide norms.

This review is constrained by the scope of databases consulted and the reliance on literature published primarily in English. These limitations may have excluded region specific studies or gray literature that provide valuable local insights into the implementation of sustainable dentistry. Additionally, the focus on peer reviewed sources may limit the inclusion of innovative practices documented in professional reports or non-traditional academic outlets. Another limitation is the variability in methodological rigor among the included studies, which may affect the generalizability of findings. The lack of longitudinal studies and comprehensive metrics also restricts the ability to assess long term outcomes of sustainability initiatives.

Future research should expand to include diverse linguistic sources and incorporate gray literature to capture a more holistic view of global sustainability efforts in dentistry. Longitudinal studies are needed to evaluate the enduring impact of educational and policy interventions. Moreover, comparative analyses across geographic regions could illuminate how cultural, economic, and institutional factors uniquely influence implementation. There is also a need to develop standardized metrics for assessing sustainability in dental practice, which could facilitate benchmarking and policy evaluation. Expanding interdisciplinary collaboration and stakeholder engagement will be essential in designing scalable, context specific solutions that promote environmental responsibility across the dental sector.

CONCLUSION

This narrative review has demonstrated the growing global commitment to integrating sustainability into dental education and clinical practice. Key findings highlight that while awareness of eco-friendly practices among dental students and professionals is increasing, implementation remains inconsistent due to systemic barriers. Educational interventions have proven effective in shaping positive attitudes

and sustainable behaviors, yet gaps in curriculum design and access to training persist. Material innovations, such as PEEK and recycled zirconia, show strong potential in reducing the ecological footprint of dental treatments without compromising clinical safety or effectiveness.

Discussion further revealed that institutional policies, economic incentives, and cultural contexts are critical factors influencing the adoption of sustainable practices. Institutions with clearly defined environmental policies and training programs report better implementation outcomes. However, high costs and lack of regulatory support continue to deter adoption. Thus, this review underscores the urgent need for comprehensive policies, financial incentives, and community engagement to enable system wide sustainability transitions in dentistry.

Future research should focus on evaluating the long term impacts of educational and material interventions and developing standardized metrics to assess sustainability in dental care. Expanding access to green technologies and fostering cross sector collaboration will be vital. Overall, integrating sustainability into dental curricula, supported by institutional commitment and public awareness, emerges as a key strategy in addressing environmental challenges in healthcare.

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