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Sustainable design in dental equipment: A Systematic review of gaps between environmental assessment and eco-design implementation

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ABSTRACT

Sustainability has become an important concern in healthcare, including dentistry, due to its environmental impact. This study aims to systematically review the current state of sustainability research in dental equipment, with a focus on identifying gaps between environmental assessment and design implementation. This study employed a systematic literature review following the PRISMA guidelines. A keyword-based search was conducted in the Scopus database with a publication range from 2016 to 2026. A total of 37 records were identified, of which 21 were screened after initial filtering. Following title, abstract, and full-text assessment, 7 studies met the inclusion criteria. Most studies focus on environmental impact assessment using Life Cycle Assessment (LCA), with key sustainability factors including energy consumption, water usage, and material selection. This study highlights a significant gap between environmental assessment and practical design implementation in dental equipment. Future research should focus on integrating LCA with eco-design approaches and incorporating context-specific factors, particularly for tropical environments, to support the development of more sustainable dental technologies.

Keywords: Sustainability; Eco-Design; Dental Equipment; Life Cycle Assessment (LCA); Green Dentistry

1. Introduction

Sustainability has become an increasingly important issue in healthcare systems worldwide, driven by growing concerns over environmental degradation, climate change, and resource scarcity [1]. The healthcare sector contributes significantly to global carbon emissions and resource consumption, and dentistry is no exception [2]. Dental practices rely on energy-intensive equipment, water-dependent processes, and a wide range of materials, all of which contribute to environmental impacts throughout their lifecycle [3].

In recent years, researchers have begun to explore sustainability in dentistry, particularly through the application of life cycle assessment (LCA). These studies have provided valuable insights into the environmental footprint of dental materials, procedures, and services, highlighting key impact areas such as energy consumption, material usage, and waste generation [4]. Despite these advances, most existing research remains focused on measuring environmental impacts, rather than addressing how such findings can inform the design and development of dental equipment [5].

At the same time, the concept of eco-design, also known as Design for Environment (DfE), has gained widespread attention in engineering and product development. Eco-design emphasizes the integration of environmental considerations into the early stages of product design, including material selection, energy efficiency, and end-of-life strategies such as reuse, recycling, and remanufacturing [6]. While these principles have been successfully applied in various sectors, their adoption in dental equipment design remains limited and fragmented.

Furthermore, most existing studies are conducted in developed regions with temperate climates, while limited attention has been given to tropical environments where high humidity, temperature, and resource variability may influence equipment performance and sustainability outcomes [7]. Given these challenges, there is a clear need to bridge the gap between environmental assessment and design implementation, while also incorporating climate-specific considerations. Integrating LCA with eco-design principles offers a promising pathway to develop dental equipment that is not only environmentally efficient but also adaptable to diverse operating conditions. However, no study has systematically examined how LCA findings are translated into eco-design strategies in dental equipment development. This reveals a critical disconnect between environmental assessment and engineering design practices. Therefore, this study aims to analyze the extent to which LCA findings have been translated into eco-design strategies in dental equipment, with a focus on life cycle assessment and eco-design strategies. In addition, this study seeks to contextualize the findings within tropical environments and propose directions for developing more climate-responsive and sustainable dental technologies.

2. Methods

This study employed a systematic literature review approach following the PRISMA guidelines to ensure transparency, consistency, and reproducibility in the study selection process. The review focused on identifying relevant studies related to sustainable design, eco-design, and environmental considerations in dental equipment and healthcare systems. The literature search was conducted using the Scopus database, selected for its extensive coverage of high-quality peer-reviewed publications across engineering, healthcare, and sustainability disciplines. Scopus also offers advanced search functionalities, consistent indexing standards, and comprehensive citation tracking, which support systematic and reproducible literature retrieval. Furthermore, its broad interdisciplinary scope makes it particularly suitable for studies that intersect technical design and healthcare sustainability.

The search strategy was developed using a combination of predefined keywords, structured into the following search query: (*"sustainable design" OR "eco-design" OR "design for environment" OR "DfE") AND ("dental equipment" OR "medical device*" OR "healthcare technolog*") AND ("life cycle assessment" OR "LCA" OR "environmental impact" OR "resource efficiency" OR "green dentistry")*. These keywords were selected to capture both engineering design perspectives and healthcare sustainability contexts. To ensure the relevance and quality of the selected studies, several limitations were applied during the search process. The publication year was restricted to the period between 2016 and 2026 to reflect recent developments in sustainability research. In addition, only peer-reviewed journal articles indexed in Scopus were considered, covering journal quartiles Q1 to Q4. These criteria were applied to ensure that the selected studies met minimum academic quality standards while maintaining a comprehensive scope.

The inclusion criteria were defined as follows: (1) studies addressing sustainability, eco-design, or environmental assessment; (2) studies related to dental equipment, medical devices, or healthcare systems; (3) peer-reviewed journal articles; and (4) publications written in English. Exclusion criteria included: (1) studies not related to design or environmental aspects; (2) articles without abstracts; (3) studies that did not meet relevance or quality standards; and (4) records filtered out through automated screening tools. The study selection process was conducted in several stages. Initially, 37 records were identified through the keyword-based search in Scopus. Prior to screening, 16 records were removed, including those marked as ineligible by automation tools (n = 6), records excluded based on journal tier considerations (n = 5), and records without abstracts (n = 5). The remaining 21 records were screened based on titles and abstracts, resulting in the exclusion of 13 studies due to lack of relevance.

Subsequently, 8 reports were sought for full-text retrieval, of which 1 report was not successfully retrieved. A total of 7 studies were assessed for eligibility and included in the final qualitative synthesis.

Data extraction was conducted using a structured approach to collect key information from each included study, including publication year, research focus, methodology, and sustainability dimensions such as energy consumption, water usage, and material selection. The extracted data were analyzed qualitatively to identify research trends, methodological approaches, and gaps in the literature, particularly in relation to the integration of eco-design and lifecycle thinking in dental equipment development. The selected studies were analyzed using a qualitative thematic analysis approach. Each article was coded based on key dimensions, including research focus, methodology, sustainability aspects (energy, water, materials), and design integration. The coding results were then grouped into thematic categories to identify patterns, trends, and research gaps. The overall study selection process is illustrated in the PRISMA flow diagram (shown in Figure 1), which presents the number of records identified, screened, excluded, and included at each stage of the review.

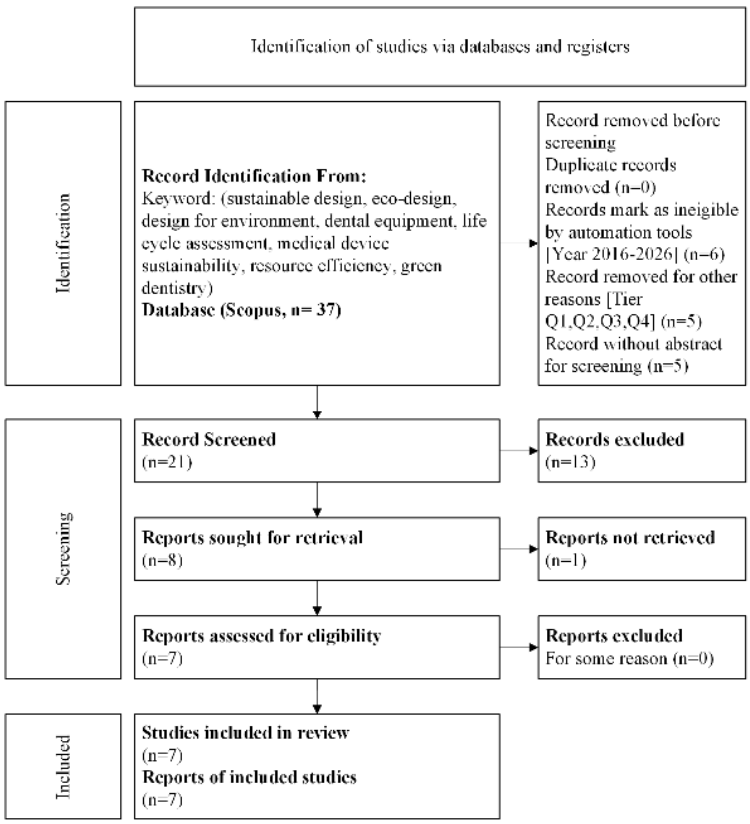

Figure 1. SLR with PRISMA flow diagram.

3. Results and Discussion

Overview of reviewed studies

The study selection process was conducted in accordance with the PRISMA framework (Figure 1). A total of 37 records were initially identified from the Scopus database using predefined keywords related to sustainable design, eco-design, dental equipment, life cycle assessment, and green dentistry. Prior to screening, 16 records were removed, including records marked as ineligible by automation tools (n = 6), records excluded based on journal ranking considerations (n = 5), and records without abstracts (n = 5). No duplicate records were identified. The remaining 21 records were subjected to title and abstract screening, during which 13 studies were excluded due to lack of relevance to sustainability, eco-design, or dental equipment design. Subsequently, 8 reports were sought for retrieval, of which 1 report was not successfully retrieved. A total of 7 studies were assessed for eligibility and met the inclusion criteria. The 7 articles were included in the final qualitative synthesis as shown in Table 1.

Table 1. Articles that meet the criteria.

No	Title	Year	Quartile	Method	Key Findings
1	Knowledge, attitude, and practice of dental professionals towards green dentistry in Karachi city: a cross-sectional survey [8].	2025	Q1	Survey	Awareness high, practice low
2	On the road to sustainability – application of metallic nanoparticles obtained by green synthesis in dentistry: a scoping review [9].	2025	Q2	Scoping review	Eco-friendly materials potential
3	Psychometric analysis of a KAP questionnaire on green dentistry using PLS-SEM and EFA: a pilot study [10].	2025	Q1	PLS-SEM	Valid model, behavior gap
4	Green Dentistry in Oral Cancer Treatment Using Biosynthesis Superparamagnetic Iron Oxide Nanoparticles: A Systematic Review [11].	2024	Q2	Systematic review	Green nanoparticles effective
5	Towards Green Dentistry: Evaluating the Potential of 4D Printing for Sustainable Orthodontic Aligners with a Reduced Carbon Footprint [12].	2024	Q1	Experimental	Reduce carbon footprint
6	The Potential Application of Green-Synthesized Metal Nanoparticles in Dentistry: A Comprehensive Review [13].	2022	Q1	Review	Sustainable alternatives
7	Green dentistry: a systematic review of ecological dental practices [14].	2019	Q1	Systematic review	Eco practices identified

Table 1 summarizes the selected studies, highlighting their methodological approaches and key findings. It can be observed that most studies focus on assessment and material innovation, while only a few address design implementation. This further supports the identified gap between environmental evaluation and engineering design in dental equipment.

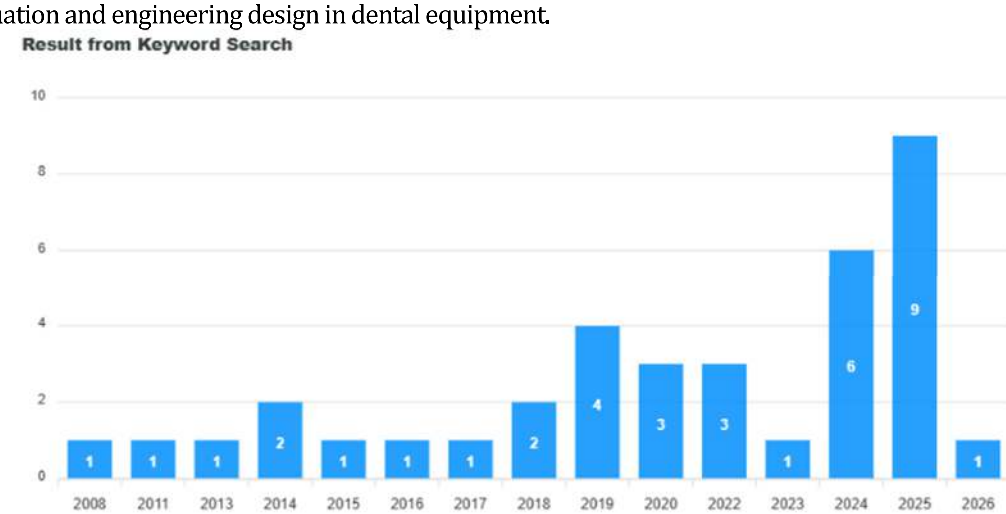

Figure 2. Trend of selected studies result from keyword search.

The temporal distribution of the selected studies indicates that research on sustainability in dentistry and healthcare has increased in recent years (shown in Figure 2). Figure 2 illustrates the increasing trend of sustainability-related research in dentistry, particularly after 2020. This trend reflects growing global awareness of environmental issues in healthcare. This trend reflects the growing global emphasis on reducing environmental impacts within healthcare systems More recent studies further highlight the integration of sustainability concepts into dental practice, including waste management, environmental awareness, and resource efficiency [15]. Despite this progress, the limited number of included studies suggests that research specifically focusing on sustainable design in dental equipment remains relatively scarce.

In terms of research focus, the included studies can be broadly categorized into three main areas: dental materials and clinical practices, healthcare system sustainability, and emerging discussions on sustainable design approaches. A significant portion of the literature focuses on evaluating environmental impacts through waste management, carbon footprint, and clinical efficiency [16]. Some studies extend this analysis to broader healthcare systems, examining energy consumption and resource use. Additionally, recent studies have begun to explore advanced materials, including polymer-based and nano-engineered materials, as potential solutions for improving environmental performance. However, only a limited number of studies explicitly address the design and development of dental equipment, indicating that this area remains underexplored.

Regarding methodological approaches, Life Cycle Assessment (LCA) was identified as the most commonly used method among the included studies [17]. LCA is widely applied to evaluate environmental impacts across the product lifecycle, including material extraction, production, usage, and disposal [18]. Other methodological approaches include literature reviews, conceptual frameworks, and case-based analyses. Some studies also highlight eco-design or Design for Environment (DfE) as an important strategy for reducing environmental impact, particularly when integrated at the early stages of product development. However, consistent with the small number of included studies, the integration of LCA with practical design implementation remains limited.

The analysis of sustainability dimensions across the included studies reveals that energy consumption, water usage, and material selection are the primary contributors to environmental impact. Energy-intensive dental equipment, such as compressors and sterilization systems, significantly contribute to carbon emissions in healthcare settings. Water usage is also identified as an important factor, particularly in cleaning and operational processes, although limited studies propose design-based solutions for reducing water consumption. These findings indicate that sustainability efforts are still largely focused on operational improvements rather than design innovation. Material usage is another key factor influencing environmental performance. Several studies emphasize the importance of sustainable material selection, including recyclable and low-impact materials, to reduce lifecycle environmental burdens. Advances in nanotechnology and smart materials also provide opportunities for enhancing performance while reducing environmental impact in medical and dental applications. Nevertheless, the application of these innovations in dental equipment design remains limited.

Research gap

Based on the synthesis of the selected studies, several critical research gaps can be identified. First, there is a clear imbalance between environmental assessment and design implementation. Most studies focus on evaluating environmental impacts using Life Cycle Assessment (LCA), while only a limited number attempt to translate these findings into practical design strategies for dental equipment. This indicates that sustainability research in dentistry remains predominantly assessment-oriented rather than solution-oriented. Second, the literature reveals a significant fragmentation between research domains. Studies related to green materials, such as nanoparticles, primarily focus on material performance and environmental benefits, whereas behavioral studies emphasize knowledge, attitude, and practice (KAP) aspects. However, these domains are rarely integrated into engineering design processes, resulting in a lack of comprehensive frameworks for sustainable dental equipment development.

Third, the limited adoption of eco-design principles suggests the presence of practical barriers. These may include regulatory constraints in medical device development, high costs associated with redesign and certification, and the lack of interdisciplinary collaboration between engineers, healthcare professionals, and policymakers. As a result, eco-design remains largely conceptual and has not been widely implemented in real-world dental equipment design. Fourth, the dominance of LCA as a methodological approach highlights a methodological gap. While LCA provides a robust framework for environmental assessment, it does not inherently offer design solutions. The lack of integration between LCA and eco-design approaches limits the ability of researchers and practitioners to develop actionable and sustainable design strategies. Finally, none of the reviewed studies explicitly consider tropical environmental conditions, such as high humidity, elevated temperatures, and variability in energy and water availability. This indicates a contextual gap, as sustainability solutions developed in temperate regions may not be directly applicable to tropical settings.

Summary and limitations

This study provides a systematic overview of sustainability research in dental equipment, highlighting the increasing attention to environmental issues in dentistry, particularly after 2020. The findings indicate that most studies rely on Life Cycle Assessment (LCA) to evaluate environmental impacts, focusing on key factors such as energy consumption, water usage, and material selection. While LCA offers a robust and standardized framework for assessment, its application remains largely limited to measuring impacts rather than informing design improvements. The review also reveals that existing research is fragmented across multiple domains, including behavioral studies (knowledge, attitude, and practice), material innovation (e.g., green-synthesized nanoparticles), and emerging technologies (e.g., 4D printing).

However, these domains are rarely integrated into a unified design framework, limiting their practical application in dental equipment development. In addition, eco-design principles are still predominantly discussed at a conceptual level, with minimal implementation in real-world engineering design. This study has several limitations. The number of included articles is relatively small (n = 7), which may limit the generalizability of the findings. The reliance on a single database (Scopus) may also introduce selection bias, as relevant studies from other sources may not be captured. Furthermore, no formal quality assessment of the included studies was conducted, and some studies focus on broader aspects of dentistry rather than specific design applications. Despite these limitations, this study provides a useful foundation for future research aimed at developing integrated and context-specific sustainable design strategies in dental equipment.

4. Conclusion

This study highlights that sustainability research in dentistry has grown significantly; however, its application in dental equipment design remains limited. Existing studies predominantly focus on environmental assessment and operational practices, with minimal integration into engineering design processes. The findings reveal a critical gap between Life Cycle Assessment and eco-design implementation, particularly in the context of tropical environments. From a practical perspective, this study suggests that dental equipment manufacturers and engineers should begin integrating sustainability considerations at the early design stage, including material selection, energy efficiency, and lifecycle thinking. From an academic perspective, this study contributes by identifying the need for an integrated framework combining LCA, eco-design, and climate-specific factors. Future research should focus on developing integrated design approaches that combine Life Cycle Assessment and eco-design principles in dental equipment development. Furthermore, incorporating climate-specific factors, particularly for tropical regions, is essential to ensure that sustainable design solutions are both effective and contextually appropriate.

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