Eco-Friendly Prosthodontic Materials and Sustainable Manufacturing Approaches

Aathmiga. S[1], Dr. Shyam Sundar[2]
[1]*Undergraduate Student – BDS, Department of Prosthodontics, Meenakshi ammal dental college and hospital, Chennai, Tamil Nadu*
[2]*MDS, Associate professor, Department of Prosthodontics, Meenakshi ammal dental college and hospital, Chennai, Tamil Nadu*

***Abstract*— The discipline of prosthodontics encompassing the design, fabrication and use of dental prostheses has traditionally relied on materials and processes that impose significant environmental burdens. These include energy-intensive manufacturing, extraction and refinement of metals and ceramics, single-use plastics, impression materials, gypsum waste, and conventional polymeric denture bases. In recent years, the concept of "green prosthodontics" has emerged: leveraging eco-friendly materials (biodegradable polymers, natural-fibre composites, and recycled metals/ceramics), digital workflows (CAD/CAM, 3D printing) and circular manufacturing strategies (recycling of gypsum, reuse of alloys, waste-minimization) to reduce the environmental footprint while maintaining clinical performance. This review summarizes current evidence and developments in sustainable materials for prosthodontics, and explores manufacturing-process innovations that support a sustainable prosthetic value chain. Key challenges including cost, regulatory barriers, material performance trade-offs and laboratory adoptions are discussed, and future directions are proposed.**

***Index Terms*— prosthodontics, eco-friendly materials, sustainable manufacturing, dental materials, circular economy**

I. INTRODUCTION

The global push toward sustainability, climate change mitigation and a circular economy calls for transformation across industries including healthcare and dentistry. The field of prosthodontics, which deals with the restoration and replacement of missing teeth (via dentures, crowns, bridges, implants, overdentures, etc.) uses a wide range of materials (metals, ceramics, polymers, impression materials, gypsum, waxes) and processes (casting, milling, sintering, 3D printing, i impression-taking, model-making) that generate waste, consume energy and rely on non-renewable resources.

Thus, there is an imperative to shift toward more sustainable, low-impact materials and manufacturing approaches in prosthodontics. This encompasses:

1. Selecting materials with lower embodied energy, higher recyclability or biodegradability
2. Adopting manufacturing workflows that reduce waste, energy use and single-use components
3. Implementing circular economy practices (reuse, recycling, remanufacturing) in dental laboratories and clinics
4. Integrating digital technologies (CAD/CAM, 3D printing) that can offer more efficient use of material and energy.

This review will explore: (a) eco-friendly materials in prosthodontics (including polymers, composites, natural fibers, recycled metals/ceramics), (b) sustainable manufacturing approaches (digital workflows, additive manufacturing, recycling of gypsum and other waste), (c) the opportunities and challenges for adoption in prosthodontic practice and laboratory environments, and (d) future outlook.

II. ECO-FRIENDLY MATERIALS IN PROSTHODONTICS

1. Polymer-based Materials and Natural-Fibre Composites:

Conventional denture bases and prosthetic frameworks frequently employ polymethyl methacrylate (PMMA) and other non-degradable synthetic polymers. These pose recycling and wastemanagement issues. Recent research has explored reinforcement of dental elastomers and impression materials with natural fibers or agricultural by-products. For example, in a recent study, a wheat-bran-reinforced elastomer composite was developed for dental impression applications, achieving comparable compressive strength (~105 MPa) and reducing cost by ~50%. The incorporation of natural filler aligns with sustainability objectives using renewable feedstocks, reducing synthetic polymer volume, and lowering disposal burden.

Further, beyond reinforcement, materials engineered for biodegradability or based on bio-polymers are gaining interest. While not yet widespread in prosthodontics, the broader additive-manufacturing literature indicates growing use of biodegradable polymers and bio-composites. Thus, the translation of these to prosthetic frameworks, denture bases or interim prostheses is a promising direction.

2. Recycled Metals and Ceramics:

Metals (e.g., cobalt-chromium, nickel-chromium, titanium) and ceramics (porcelains, zirconia etc.) have high embodied energy and often leave waste streams. One sustainability approach is the reuse or recycling of metallurgical alloys within dental labs and casting facilities. Although specific published data for prosthodontic alloys is limited, the notion of circular-economy metal use is highlighted in the broader dental sustainability literature. Ceramic materials pose a challenge since their processing (high-temperature sintering) is energy-intensive; however, developing more efficient sintering protocols or lower-temperature ceramic composites may reduce environmental burden.

3. Gypsum, Model Materials and Waste Reduction:

Dental models and prosthesis fabrication frequently use gypsum (calcium sulfate hemihydrate) for impressions, casts and models. Disposal of large amounts of gypsum waste is an environmental liability.

Studies showed that on recycling gypsum can be recycled up to three times with minimal loss of mechanical performance when processed appropriately (grinding, heat-treatment), offering a viable route toward waste-minimisation. This illustrates how even long-standing materials may be managed more sustainably.

4. Nanotechnology, Additives and Green Synthesis:

Though not strictly eco-friendly in terms of feedstock, materials modified with nanotechnology can sometimes lead to longer lifespans, less frequent replacement, and potentially reduced material volume indirectly supporting sustainability. For example, silver-nanoparticle-doped polymers provide antimicrobial action and may reduce prosthesis failure or replacement rates. Moreover, the synthesis of nanoparticles via green (plant-based) routes further aligns with sustainability. However, one must consider the full life-cycle impact (toxicity, recyclability) of nanomaterials.

III. SUSTAINABLE MANUFACTURING APPROACHES IN PROSTHODONTICS

1. Digital Workflows: CAD/CAM and Intra-oral Scanning:

Digital impressions, CAD design and CAM milling or additive manufacturing reduce dependence on physical impression materials, stone models and manual adjustments—thereby reducing waste of impression materials, trays, model stone and shipping. Digital workflows also enable more accurate fabrication, reducing remakes and material discard.

2. Additive Manufacturing (3D Printing) with Eco-Friendly Materials:

Additive manufacturing (AM) or 3D printing presents several sustainability advantages: minimal waste (only the material used to create the object), potential for complex geometries with less material, shorter supply chains, and compatibility with biodegradable/bio-based resins. Within prosthodontics, 3D printing is increasingly used for models, provisional crowns/bridges, dentures and even frameworks. Selecting recyclable or biodegradable feedstocks combined with digital workflows supports an eco-friendly manufacturing chain.

3. Recycling, Remanufacturing and Circular Economy Approaches:

In laboratories and clinics, substantial waste is generated: impression trays, single-use plastics, gypsum casts, metal sprues, etc. Implementing internal recycling streams—for example, grinding and re-processing gypsum, recycling alloy scrap, using reusable trays or biodegradable alternatives—can significantly reduce the environmental footprint.

4. Energy Efficiency and Waste Minimisation in Laboratories:
Dental laboratories often employ casting units, furnaces, milling machines, and sintering ovens—all energy-intensive. Transitioning to energy-efficient equipment (LED lighting, better insulation, more efficient furnaces), scheduling batching strategies, reducing idle time, and optimizing logistics (local manufacturing, shorter transport) contribute to sustainability.

5. Material Selection Policy, Procurement and Supply Chain:
Sustainable manufacturing also implies greening the supply chain: selecting suppliers of eco-friendly materials, favoring vendors with recycling programs, reducing packaging, preferring reusable rather than single-use items. Green procurement is highlighted as a key factor in sustainable prosthodontics.

IV. INTEGRATION: ECO-MATERIALS + SUSTAINABLE MANUFACTURING — A PROPOSED FRAMEWORK

Below is a suggested framework for integrating eco-friendly materials with sustainable manufacturing in prosthodontic practice:

1 Material Audit: Evaluate current usage (polymers, impression materials, gypsum, alloys, and ceramics) for embodied energy, recyclability, waste generation.
2 Material Substitution: Where feasible, replace high-impact materials with eco-friendly alternatives (e.g., natural-fibre composites for impressions, biodegradable polymer denture bases, and recycled alloy frameworks).
3 Digital Workflow Adoption: Shift from physical to digital impression and manufacturing (intra-oral scanning → CAD design → CAM/3D print) to reduce material waste and transport.
4 Additive Manufacturing with Eco-Feedstocks: Use 3D printing with properly certified biodegradable or recycled resins/filaments for models, Provisionals or even final prostheses where validated.
5 Closed-Loop Recycling: Establish on-site or laboratory recycling programs: e.g., process gypsum waste for reuse, reclaim alloy scraps, reuse trays or move to biodegradable trays.
6 Energy & Process Optimization: Upgrade lab equipment, schedule equipment uses efficiently, batch jobs to reduce idle energy consumption, consider solar or renewable energy where feasible.
7 Purchasing & Supply Chain: Adopt green procurement practices—select suppliers offering sustainable packaging, recycled materials, lower-carbon transport, and reusable items.
8 Training & Awareness: Educate prosthodontists, dental technicians and staff about material sustainability, waste minimization, digital workflows and environmental impact.
9 Monitoring & Metrics: Set measurable targets (e.g., kg of gypsum recycled/year, % of impressions digital, energy kWh per prosthesis, carbon-equivalent emissions) and review periodically.
10 Patient Engagement & Marketing: Communicate to patients that the practice is engaged in “green prosthodontics” (sustainable materials, digital workflows, lower-waste lab) as part of differentiating care and raising awareness.

V. EVIDENCE, BENEFITS AND LIMITATIONS

Benefits

1. Reduced environmental impact: Less waste (materials, packaging, scrap), lower carbon footprint from shorter supply chains and efficient workflows. Resource conservation: Use of renewable or recycled materials reduces extraction of virgin resources.
2. Cost-savings (in long term): While some sustainable materials may cost more initially, reduction in waste, re-processing and more efficient workflows may yield cost savings. For example, in the wheat-bran composite study cost was halved.
3. Enhanced public/professional image: Aligns with global sustainability goals (e.g., UN SDGs) and may appeal to environmentally conscious patients.
4. Laboratory efficiency: Digital workflows and 3D printing can reduce remakes, reduce

shipping/transport, and improve speed and accuracy.

Limitations & Challenges

1. Material performance trade-offs: Biodegradable or natural-fibre composites may have reduced mechanical properties (e.g., lower tensile strength) compared to conventional materials. In the wheat-bran example tensile strength dropped from 11 MPa to 7 MPa.
2. Higher initial costs and investment: Digital equipment, 3D printers, new eco-materials may require higher capital expenditure. As stated earlier high initial costs can limit adoption.
3. Regulatory and certification hurdles: New materials require clinical validation, biocompatibility certification and long-term performance data, which slow adoption.
4. Lab and clinician training needs: Shifting to digital workflows and eco-materials requires training and change-management.
5. Recycling infrastructure and logistics: Dental labs and clinics may lack infrastructure for recycling (e.g., alloy scrap, gypsum re-processing) or may find logistical and regulatory constraints.
6. Material cost-vs-availability: Some eco-friendly materials may not yet be widely available or cost-effective in all jurisdictions (particularly in low- and middle-income countries).
7. Life-cycle assessment (LCA) data paucity: Comprehensive life-cycle assessments for many new dental materials are lacking; we must ensure that "eco-friendly" claims are substantiated rather than greenwashed. The cellulose modification warns that renewability alone isn't enough—they must meet all sustainability criteria.

VI. FUTURE DIRECTIONS AND RESEARCH NEEDS

1. Development of high-performance biodegradable prosthodontic materials: There is a need for denture base polymers, framework materials and prosthetic silicones that are biodegradable/compostable or fully recyclable, yet meet the mechanical/biological demands of prosthodontics.
2. Life-cycle assessment (LCA) studies specific to prosthodontic materials: Quantify embodied energy, carbon footprint, toxicity, end-of-life fate for different materials (conventional vs eco-friendly) to guide choices.
3. Scaling additive manufacturing with bio-based/resin feedstocks for final prostheses: Moving beyond provisional parts into definitive prostheses manufactured with eco-friendly materials and validated for long-term clinical use.
4. Closed-loop systems in dental labs/clinics: Research and pilot studies on feasible recycling infrastructure (gypsum waste, alloy scrap, resin/print waste) in prosthodontic laboratories. The recycling of gypsum up to three cycles has already been demonstrated.
5. Cost-benefit and business-model analyses: Evaluate the economics of green prosthodontics in different settings (private practice, public clinics, and low-resource settings) to identify feasible pathways.
6. Regulatory and standardization pathways for eco-materials in dental prosthetics: Encourage regulatory agencies and dental associations to incorporate sustainability criteria into material approvals, procurement guidelines and practice standards.
7. Educational integration: Embedding sustainable dentistry and green prosthodontics into undergraduate/postgraduate curricula so that new practitioners are trained with environmental consciousness.
8. Patient-centered research on acceptance: Explore patient perceptions of sustainable prosthodontic practices/materials (e.g., willingness to pay, acceptance of eco-materials) which will drive demand and market availability.
9. Monitoring of long-term clinical performance: Ensure that eco-friendly materials maintain durability, biocompatibility and functional outcomes comparable (or superior) to conventional materials

VII. CONCLUSION

The shift toward eco-friendly prosthodontic materials and sustainable manufacturing approaches is not only desirable but necessary in the context of global environmental challenges. The combination of novel materials (natural-fibre composites, biodegradable/resin-based materials, and recycled metals/ceramics) with lean, digital, additive and circular manufacturing approaches holds considerable promise in reducing the environmental footprint of prosthodontic practice, while preserving or enhancing clinical performance. However, adoption remains at an early stage, hindered by cost, regulatory, training and infrastructure barriers. A concerted effort—spanning material development, life-cycle assessment, laboratory practice redesign, education and supply-chain innovation—is required to realize the vision of "green prosthodontics". For practitioners, laboratories and dental educators, the time to begin integrating sustainability into everyday prosthodontic workflows is now.

REFERENCES

[1] Shinkai RSA, Biazevic MGH, Michel-Crosato E, de Campos TT. J Prosthet Dent

[2] Tawade SU, Dhamande MM, Dubey SA, Sathe S, Selukar MS, Pathak A. Sustainable dentistry: A comprehensive review of the recycling techniques for gypsum products in prosthodontics. Cureus

[3] Agrawal K, Bhat AR. Advances in 3D printing with eco-friendly materials: A sustainable approach to manufacturing. RSC Sustainability

[4] Prakash P, Gowda EM. Green prosthodontics: Need of the hour. IP Ann Prosthodont Restor Dent

[5] Aboamer MA, Almutairi AR, Alassaf A, Alqahtani TM, Almutairi TF, Saijari GN, Mohamed NAR.Innovative and eco-friendly natural fibre composites for dental impression materials: A study on wheat bran reinforcement. Polymers (Basel)