Journal of Neonatal Surgery
ISSN(Online): 2226-0439
Vol. 14, Issue 18s (2025)
https://www.jneonatalsurg.com

The Future of Dental Materials: Biocompatible and Sustainable Polymers

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Cite this paper as: Bharti Raina, Dinesh Deshwal, Nitesh Singh, Ravi Kumar Deshwal, Sumira Malik, Sarvesh Rustagi, et.al (2025) The Future of Dental Materials: Biocompatible and Sustainable Polymers. *Journal of Neonatal Surgery*, 14 (18s), 32-42.

ABSTRACT
Extensive research into creating materials produced from renewable sources has been prompted by the depletion of petroleum-based resources, the detrimental effects of industrial processes, and growing environmental awareness. Dental materials research and development are essential to clinical dentistry. Sustainable, biodegradable, and environmentally friendly substitutes for traditional polymers are becoming more and more popular due to growing environmental awareness and legal requirements. The use of biopolymers in dentistry is examined in this review along with a comparison to traditional polymers. Epoxy resin, one of the most popular resins in dental materials, is given special attention. Its function as an epoxy resin-based sealer is examined, as well as its thermal, chemico-physical, biocompatible, and viscoelastic characteristics. Even while newly mixed epoxy resin is known for its superior sealing and physical qualities, it has strong cytotoxic effects on osteoblasts. Since biopolymers produced from sustainable sources have shown improved biomechanical qualities, this review emphasizes the necessity of creating environmentally friendly epoxy resins from renewable resources in order to lessen these consequences.

Keywords: Sustainable, Biocompatible, Dental, Resin.

1. INTRODUCTION

The rapid industrialization driven by chemical-based processes and energy-intensive technologies has significantly contributed to health hazards, environmental degradation, declining agricultural biodiversity, and ecosystem loss. The widespread distribution of petrochemical pollutants has led to severe air, water, and soil contamination, including heavy metal pollution, sludge accumulation, greenhouse gas emissions, ozone depletion, smog formation, acid rain, and climate change—resulting in extensive ecological damage (Zhao et al., 2024). These growing environmental and societal pressures are accelerating the transition from fossil fuels to renewable and sustainable energy sources (Wang et al., 2024).

In response to these challenges, scientists and technologists are actively exploring alternative, sustainable energy systems and their applications in processing renewable materials such as eco-friendly polymers. Achieving a balance between economic growth, social inclusion, and environmental protection has made sustainable development essential. This has driven interdisciplinary research and technological advancements in fields like oleo-chemistry, biosciences, biotechnology, bioengineering, and medical sciences to develop and refine eco-friendly specialty chemicals derived from renewable natural resources (Liu et al., 2024).

Sustainable polymers, derived from renewable sources such as starch, lignin, proteins, cellulose, shellac, rosin, polyhydroxyalkanoates, furanone, alginate, wool fibers, and vegetable oils, are free from volatile organic compounds (VOCs) and have a wide range of industrial applications. These include use as plasticizers, lubricants, adhesives, printing inks, paints, and coatings (Papageorgiou, 2018). Additionally, polymers play a crucial role in dentistry, contributing to preventive, restorative, and regenerative treatments due to their exceptional physical, mechanical, and biological properties (Rokaya et al., 2018).The development of sustainable, biocompatible polymers represents a critical step toward reducing environmental impact while enhancing technological applications in various industries, including dentistry.

Conventional Synthetic Resins

Synthetic resins are industrially manufactured substances, typically non-crystalline or viscous, that transform into rigid polymers through a curing process. To facilitate curing, these resins contain reactive end groups such as acrylates or epoxides. While some synthetic resins share properties with natural plant resins, many exhibit distinct characteristics (Davoodi et al., 2024).

Synthetic resins can be categorized into several classes. Some are produced through the esterification of organic compounds, while others function as thermosetting plastics. In thermosetting systems, the term "resin" is often applied to either the reactant, the product, or both. In the case of epoxy resins, one of the monomers is referred to as the "resin," while the other is known as the "hardener."

For thermosetting plastics that require only a single monomer, the monomer itself is typically referred to as the "resin." For instance, liquid methyl methacrylate (MMA) is commonly called "resin" or "casting resin" in its liquid state. Once polymerized and set, the resulting poly(methyl methacrylate) (PMMA) is better known as acrylic glass or simply acrylic—the same material marketed under trade names like Plexiglas and Lucite (Shundo et al., 2022).

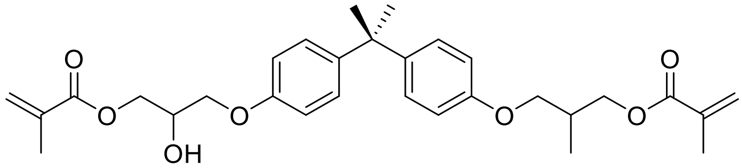


Fig. 1: Vinyl ester resin

2. TYPES OF SYNTHETIC RESINS

Synthetic resins are classified into several categories based on their chemical composition and method of production, such as esterification or saponification of organic compounds (Chowdhury et al., 2020). The major types of synthetic resins include:

- Polyesters: Saturated and Unsaturated Polyesters
- Alkyd Resins
- Epoxy Resins
- Acrylics
- Vinyl Resins
- Polyacetals
- Polyurethanes
- Amino Resins
- Phenolic Resins
- Rosin-Modified Resins
- Maleic Resins
- Ketonic Resins
- Isocyanate Adducts
- Polyamides
- Silicone Resins
- Cellulose-Based Resins: Cellulose Acetate Butyrate, Nitrocellulose, Hydroxyethyl Cellulose, Carboxymethyl Cellulose
- Chlorinated Polypropylene

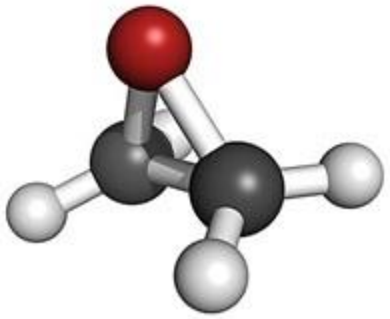
These resins are available in various physical forms, including solid, liquid, emulsion, and dispersion, making them highly adaptable for different industrial and commercial applications.

3. VERSATILITY OF EPOXY RESIN

The term "epoxy," "epoxy resin," or "epoxide" (also known in Europe as α-epoxy or 1,2-epoxy) refers to a broad class of reactive compounds distinguished by the presence of an oxirane (epoxy) ring. This three-membered ring consists of an oxygen atom bonded to two carbon atoms that are already linked within a molecular structure.

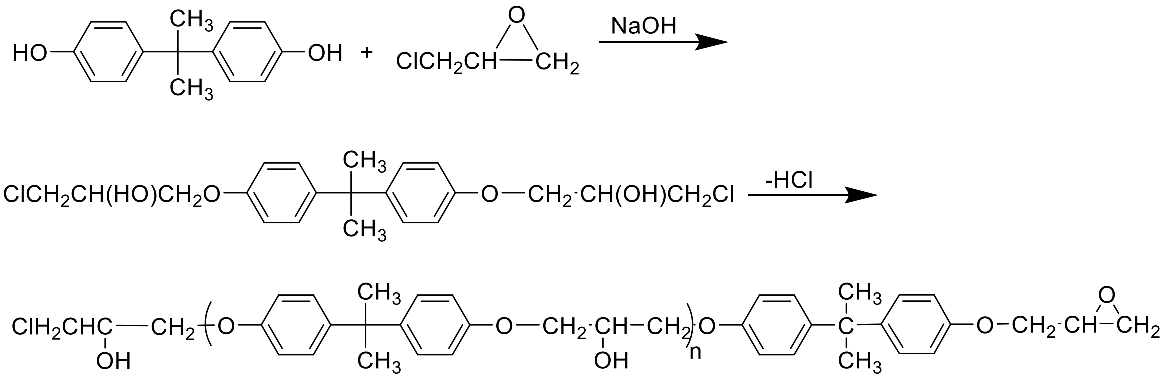
Epoxy resins are highly versatile and can be tailored for specific applications by combining them with various curing agents and modifiers. They are typically synthesized through the reaction of compounds containing at least two active hydrogen atoms (such as polyphenolic compounds, diamines, amino phenols, heterocyclic imides and amides, and aliphatic diols) with epichlorohydrin.

Due to their adaptability, epoxy resins are widely used in coatings, adhesives, composites, electronics, and various engineering applications, offering excellent mechanical strength, chemical resistance, and durability (Karak, 2021).



4. EPOXY RESIN

Epoxy resins are tough, chemically resistant, and dimensionally stable polymers known for their strong adhesion, flexibility, and compatibility with various substrates. They cure easily and exhibit excellent surface wetting properties, making them particularly suitable for composite applications. Additionally, epoxy resins are frequently used as modifiers for other polymers, such as polyurethane and unsaturated polyesters, to enhance their physical and chemical properties. One of the most widely used epoxy resin monomers is diglycidyl ether of bisphenol A (DGEBA), which serves as a key component in numerous industrial and commercial applications (Shimada et al., .2024)



Synthesis of Epoxy Monomer from Bisphenol A and Epichlorohydrin (Kireev et al., 2019)

Key Properties of Epoxy Resin (Karak et al., 2021**):**
1. High strength
2. Low Shrinkage
3. Excellent adhesion to various substrates
4. Effective electrical insulation
5. Chemical and solvent resistance, and
6. Low cost and low toxicity

Applications for epoxy resins are extensive and include (Shundo et al., 2022**):**
1. Paints and coatings.
2. Adhesives.
3. Composite materials such as those using carbon fibre and fiberglass reinforcements.
4. Industrial tooling and composites.
5. Electrical systems and electronics.
6. Consumer applications.
7. Marine applications.
8. Aerospace applications.
9. Biology.
10. Art.

Aside from the properties mentioned above, epoxy resins have two main drawbacks which are their brittleness and moisture sensitivity.

5. EPOXY COMPOSITES: ADDITIVES FOR HIGH PERFORMANCE

Fillers also play an important role in epoxy resin formulations. Reinforcing fibers such as glass, graphite and polyaramid improve mechanical properties to such an extent that epoxies can be used in many structural applications. Other non-reinforcing fillers include:
1. Powdered metals to improve electrical and thermal conductivity
2. Alumina for thermal conductivity

3. Silica for cost reduction, and strength enhancement
4. Mica – electrical resistance
5. Talc and calcium carbonate – cost reduction
6. Carbon and graphite powders to increase lubricity

Nanoparticle-reinforced epoxy composites have also generated considerable industrial interest over past decades. These materials have high specific strength-to-weight ratio, low density, and enhanced high modulus, which permits them to contend with selected metals. The primary aim of reinforcing-blending of epoxies is to achieve the desired properties while maintaining low costs. Increasing filler content generally increases viscosity and makes processing more difficult. Specific gravity usually increases, although some fillers like hollow glass or phenolic micro balloons create syntactic foams of significantly reduced density. (Rath et al., 2024)

6. OTHER IMPORTANT MODIFIERS USED IN EPOXY RESIN FORMULATIONS ARE:

Rubber Additives – They are used to increase flexibility, fatigue resistance, crack resistance, toughness in epoxy resins. The liquid rubbers most often used in epoxy composites are carboxyl-terminated butadiene acrylonitrile copolymer (CTBNs). However, the acrylonitrile content of the rubber is an important consideration when using a rubber modifier. As the nitrile content of a rubber increases, its solubility increases and eventually particle size in the cured matrix decreases. Unreactive rubbers are not used in epoxy composites applications (Banan et al., 2024).

Thermoplastic Additives – They are used to increase the fracture toughness of epoxy resins. Only relatively low MW TPs can be dissolved in epoxy resins. Commonly used thermoplastics are phenoxy, polyether block amides, PVB, polysulfone, polyethersulfone, polyimide, polyetherimide, nylon. As compared to rubbers, thermoplastics are more effective tougheneres in highly cross-linked matrices and they do not tend to affect Tg and modulus (Dzhangurazov et al., 2025**)**.

Flame Retardants – They are added to epoxy resins to incorporate FR characteristics. The presence of halogens and char-forming aromatics in the epoxy-curative based resin decreases flammability (Wang et al., 2024).

Colors and Dyes – A wide variety of colorants can be used with epoxies such as inorganic pigments except chrome greens, natural siennas, zinc sulfide white etc. and organic pigments such as carbon blacks (Zheng et al., 2017).

Epoxy Resins vs Polyester Resins (Mula et al., 2023)

Epoxy	Polyester
Extremely strong and good flexural strength The hardener and the temperature determine epoxy resin cure time Resistant to wear, cracking, peeling, corrosion and damage from chemical and environmental degradation Has a bonding strength of up to 2,000 psi Epoxy is moisture resistant after curing	Brittle and prone to micro-cracking Generally, costs slightly less than epoxy resin Off-gases VOCs and has strong, flammable fumes Bonding strength of polyester resin is generally less than 500 psi Once cured, polyester resin is water permeable, meaning water can pass through it eventually

Overall, Epoxy resins have performance advantages over polyester and vinyl esters in five major areas (Acordi et al., 2025**):**

1. Better adhesive properties (the ability to bond to the reinforcement or core)
2. Superior mechanical properties (particularly strength and stiffness)
3. Improved resistance to fatigue and micro cracking
4. Reduced degradation from water ingress (diminution of properties due to water penetration)
5. Increased resistance to osmosis (surface degradation due to water permeability)

Aside from the properties mentioned above, epoxy resins have two main drawbacks which are their brittleness and moisture sensitivity (Niaki et al., 2022).

7. HEALTH HAZARDS OF EPOXY RESINS

The primary risk associated with epoxy use is often related to the hardener component and not to the epoxy resin itself. Amine hardeners in particular are generally corrosive, but may also be classed as toxic or carcinogenic/mutagenic. Aromatic amines present a particular health hazard (most are known or suspected carcinogens), but their use is now restricted to specific industrial applications, and safer aliphatic or cycloaliphatic amines are commonly employed (Chen et al., 2025).

Liquid epoxy resins in their uncured state are mostly classed as irritant to the eyes and skin, as well as toxic to aquatic organisms. Solid epoxy resins are generally safer than liquid epoxy resins, and many are classified non-hazardous materials. One particular risk associated with epoxy resins is sensitization. The risk has been shown to be more pronounced in epoxy resins containing low molecular weight epoxy diluents. Exposure to epoxy resins can, over time, induce an allergic reaction. Sensitization generally occurs due to repeated exposure (e.g. through poor working hygiene or lack of protective equipment) over a long period of time. Allergic reaction sometimes occurs at a time which is delayed several days from the exposure. Allergic reaction is often visible in the form of dermatitis, particularly in areas where the exposure has been highest (commonly hands and forearms). Epoxy use is a main source of occupational asthma among users of plastics. Bisphenol A, which is used to manufacture a common class of epoxy resins, is a known endocrine disruptor (Duraccio et al., 2025) .

8. IS EPOXY CANCEROUS?

Epoxy products are known skin sensitizers (allergens) and can cause irritation or allergic reactions upon prolonged exposure. One of the key components in epoxy resin monomers, epichlorohydrin, is classified as a Category 1B carcinogen by the European Union (EU), meaning it is presumed to be carcinogenic to humans based on sufficient evidence from animal studies (Patel et al., 2025).

While fully cured epoxy resins are generally considered stable and inert, uncured epoxy components—especially hardeners and monomers—can pose health risks, including potential carcinogenicity. Proper handling, protective measures (such as gloves and ventilation), and adherence to safety guidelines are essential to minimize exposure risks (Santra, 2025).

9. BIOCOMPATIBILITY OF EPOXY RESIN-BASED DENTAL MATERIALS

Biocompatibility is a multidisciplinary field encompassing bioengineering, biochemistry, molecular biology, and tissue engineering. The biocompatibility of a material depends on its physical function and biological response and is essential for ensuring that it interacts harmoniously with surrounding tissues without causing short-term or long-term adverse effects (Humzum et al., 2021).

A national survey in the UK identified dental resins as a leading cause of adverse reactions among dental technicians and patients. Over 12% of reported adverse reactions in patients were linked to resin-based dental materials (Laubach et al., 2023). These adverse effects are classified into:

- Local Reactions: Mucosal toxicity and pulpal toxicity
- Systemic Reactions: Immune or toxic responses affecting overall health (Keyvan Moharam)

  Biocompatibility Concerns of Epoxy Resin-Based Root Canal Sealers

  Studies evaluating epoxy resin-based root canal sealers, such as AH26 and AH Plus, indicate dose-dependent astrocyte toxicity. Additionally, moderate cytotoxic effects have been observed on osteoblast-like cells. Research suggests that certain epoxy resin-based sealers may contribute to cellular degeneration and delayed wound healing in periapical tissues. The cytotoxicity of these materials is believed to stem from chemical elements and heavy metals released during the setting process (Shome et al., 2024).

  Key findings on AH Plus sealer include:
- Contains aluminum and iron, which may contribute to cellular toxicity.
- Exhibits initial toxicity when freshly mixed, which gradually decreases upon setting.
- Higher cytotoxicity is attributed to the release of minute amounts of formaldehyde during polymerization.
- The epoxy resin component in AH Plus may lead to DNA strand breaks, potentially affecting cellular integrity.

The presence of heavy metals in AH Plus and their potential clinical implications require further investigation. Additionally, oral and mucosal adverse reactions to resin-based dental materials have been reported.

10. ADVANCEMENTS IN EPOXY THERMOSETTING COMPOSITES AND RECYCLING CHALLENGES

Epoxy thermosetting composites are high-performance materials widely used across various industries. However, one of their major challenges is recycling, as thermosets are inherently difficult to break down and reform. Despite these challenges, significant research and technological advancements have been made to develop recyclable thermoset systems, enabling these plastics to be reprocessed to some extent.

Although recyclable epoxy thermosets have been developed, their commercial potential remains largely untapped. Meanwhile, growing environmental concerns have spurred interest in bio-based thermosetting resins, offering a sustainable alternative to conventional petroleum-derived thermosets (Klingler et al., 2023).

Bio-based thermosetting epoxy resins (**dinu et al., 2024**)

Several bio-sourced thermosetting resin systems have gained attention due to their environmental benefits, including:

1. Natural Oil-Based Epoxies – Derived from soybean, linseed, castor, and other plant oils.
2. Isosorbide-Based Epoxies – Utilizing isosorbide, a renewable diol with high rigidity.
3. Furan-Based Epoxy Systems – Developed from furans, offering sustainable and durable alternatives.
4. Phenolic and Polyphenolic Epoxies – Derived from bio-sourced phenolic compounds.
5. Epoxidized Natural Rubber – A renewable rubber-based epoxy with enhanced flexibility.

6. Epoxy Lignin Derivatives – Utilizing lignin, a major component of plant biomass, as a sustainable precursor.
7. Rosin-Based Resins – Derived from natural rosin, offering improved adhesion and durability.

Synthetic vs Natural Polymers (Satchanska et al., 2024**)**
Polymers are broadly classified into two types: natural and synthetic.

- Synthetic polymers are man-made and derived from petroleum-based resources through chemical processes. Common examples include nylon, Terylene, polyethylene, polyester, Teflon, and epoxy resins.
- Natural polymers are obtained from biological sources such as plants and animals. These include natural rubber, silk, wool, DNA, cellulose, and proteins.
  Natural and Synthetic Rubber
  Rubber exists in both natural and synthetic forms.
- Natural rubber is harvested as a latex (milky fluid) from rubber trees and is primarily composed of isoprene units with minor impurities. However, in its raw state, natural rubber tends to be sticky, perishable, and lacks durability.
- Synthetic rubber is chemically synthesized from monomers such as isoprene and offers improved mechanical properties and stability compared to natural rubber.

Vulcanization: Enhancing Rubber Properties
To improve the properties of natural rubber, a process called vulcanization (curing) is applied. This process involves heating rubber with sulfur, which forms cross-links between polyisoprene chains, significantly enhancing resilience, elasticity, and durability. Vulcanized rubber is widely used in automotive tires, industrial belts, and various commercial applications due to its superior strength and flexibility.

Pectin: A Natural Polysaccharide
Pectin is a natural polymer composed of pectic acid and pectinic acid molecules, classified as a polysaccharide due to its sugar-based structure. It is extracted from citrus peels and apple residues and plays a crucial role in plant structure by binding plant cells together. Pectin is widely used in food processing as a gelling agent, particularly in jams, jellies, and fruit preserves. Both natural and synthetic polymers have unique properties and applications. While synthetic polymers offer durability and versatility, natural polymers provide biodegradability and eco-friendliness. Advances in polymer science continue to enhance the performance and sustainability of both types, ensuring their continued relevance across various industries (Riyamol et al., 2023).

Vegetable oils
Vegetable Oils as a Sustainable Resource for Polymer Development and Dental Applications-Vegetable oils are non-toxic, biodegradable, renewable, and abundantly available, making them an eco-friendly alternative to petroleum-based resources. Their ability to form high-performance polymers enables them to compete with fossil fuel-derived materials, particularly in industries such as paints, coatings, and other commercial applications (Ribeiro et al., 2022). Historically, vegetable oils played a key role in paints and coatings, dating back to the era of cave paintings (Fakhri et ., 2024).
Potential of Vegetable Oil-Based Polymers-Over time, vegetable oil-based materials have been developed and tailored for specific end-user applications, demonstrating significant global potential in industrial coatings. Despite extensive research on their usage in paint and polymer industries, their applications in Dentistry remain underexplored. Given their unique chemical properties, vegetable oil-derived epoxy resins and polymers could play a transformative role in precision-based healthcare applications, particularly in dental materials (Silva et al., 2023).
Need for Research in Dental Sciences-A comprehensive review of the chemistry, applications, and potential of vegetable oil-based epoxies in dentistry is essential. Their integration into dental coatings and restorative materials could contribute to reducing dependence on petrochemical-based products, promoting sustainability in dental science and materials (Saraswat et., 2024). As industries continue to shift towards green chemistry and renewable resources, vegetable oil-based polymers hold immense promise for advancing sustainable, biocompatible, and high-performance materials across various sectors, including healthcare and dentistry.

Status of Biopolymer as Dental material (Hatton et al., 2022**)**
Patients seeking cosmetic and biocompatible dental restorations, especially for anterior teeth, often prefer direct filling materials due to their cost-effectiveness and time efficiency. Direct aesthetic restorations can be categorized into:

1. Silicates (introduced in the 1800s)
2. Acrylic Polymers
3. Dimethacrylate Polymers (Composite Resins) (introduced in the 1960s)
4. Ionomer Restoratives (introduced in 1972)

Among these materials, composite resins have proven superior to conventional acrylic resins, particularly in wear resistance. They are primarily used for Class III, IV, and V cavity restorations in anterior teeth, veneering of labial tooth surfaces, and, more recently, limited occlusal restorations.

Comparison of Composite Resins and Ionomers-Clinical studies indicate that ionomers demonstrate better retention than composites in cervical erosion regions. These materials are available in various colored powder forms and consist of aluminosilicate glass flour combined with aqueous solutions of acrylic acid polymers and copolymers.

11. MATERIALS USED IN DENTISTRY

Dentistry employs a wide array of materials, including (Abraham et al., 2023**):**

- Metals and Alloys: Titanium (Ti), nickel-titanium (Ni-Ti), stainless steel, cobalt-chrome alloys, nickel-chrome, gold-based alloys, and dental amalgam.
- Resins and Cements: Composite materials composed of a resin matrix, inorganic fillers, coupling agents, and additional components.
  Despite their widespread usage, composite resins have certain limitations, including:
- Polymerization shrinkage, leading to marginal leakage and secondary cavities.
- High technique sensitivity, requiring skilled application and a completely dry working environment.
- Risk of chipping and lower toughness compared to other restorative materials.

Biomaterials in Dentistry: Past, Present, and Future (Zaokari et al., 2020**)**

Biomaterials, defined as natural or synthetic substances used to augment, replace, or repair body tissues, include metals, polymers, ceramics, and hybrid materials. The development of biomaterials in dentistry has followed three generations:

1. First-Generation: Bioinert materials such as silicone rubber, polyethylene (PE), acrylic resins, polyurethanes, polypropylene (PP), and polymethyl methacrylate (PMMA).
2. Second-Generation: Bioactive and biodegradable materials, including polyglycolide (PGA), polylactide (PLA), polydioxanone (PDS), polycaprolactone (PCL), polyhydroxybutyrate (PHB), and chitosan-based polymers. These materials degrade in a controlled manner, allowing for tissue regeneration.
3. Third-Generation: Advanced biomaterials designed to induce specific biological responses at the molecular level by integrating bioactivity and biodegradability. These bioabsorbable materials can become bioactive, enhancing tissue compatibility and functionality.

The Role of Polymers in Dentistry

Polymers have become an essential component of modern dentistry, with applications in:

- Denture bases (e.g., PMMA, Bakelite, PVC)
- Soft denture liners
- Resin cements
- Pit and fissure sealants
  The introduction of methacrylate resins in 1937 revolutionized dental materials, leading to extensive research by Paffenbarger, Nelsen, Sweeney, and Coy into polymethyl methacrylate (PMMA).

Epoxy Resins in Dentistry (Cho et al., 2022**)**

Epoxy resins were initially explored in dentistry with the goal of creating a material that:

- Mimics the thermal expansion coefficient of natural tooth structure
- Provides strong adhesion to tooth surfaces
- Ensures color stability
- Exhibits insolubility in the oral environment

With continuous advancements in material science, modern dental materials have evolved to enhance aesthetics, biocompatibility, and durability. The integration of novel biomaterials aims to overcome existing challenges, ensuring long-lasting and high-performance dental restorations.

12. POLYMERS AND DENTAL HEALTH CARE

In the modern era of commercialization and technological advancement, humanity has increasingly recognized the importance of sustainability and the need to care for the environment. The extensive use of chemicals in science and technology has driven the demand for eco-friendly alternatives, including natural product-based compositions. These sustainable materials have been explored across various scientific domains, including the high-precision field of dentistry. While significant progress has been made, ongoing research continues to refine and enhance these materials to meet the evolving needs of dental care (Adnan et al., 2024).

Not all polymers have been extensively examined for dental applications, yet certain materials have demonstrated promising potential. Among them, methyl methacrylate resin, introduced to dentistry in 1937, has been one of the most extensively studied and widely used dental materials. The properties of polymethyl methacrylate (PMMA) were thoroughly investigated by Paffenbarger, Nelsen, Sweeney, and Coy, who identified several limitations, including:

- A coefficient of thermal expansion that differs from natural tooth structure
- Suboptimal adhesion to tooth surfaces

- Limited color stability in direct filling resins
  Similarly, silicate cements, another commonly used material, exhibited challenges such as solubility and disintegration in the oral environment. These shortcomings prompted researchers to explore synthetic resins beyond methyl methacrylate as potential dental filling materials. However, many available resins were unsuitable due to factors such as:
- Incompatibility with inert fillers
- High curing temperatures
- Inadequate color matching for dental applications
  Exploration of Epoxy Resins in Dentistry
  Amidst these challenges, the epoxy resin emerged as a promising material worthy of further investigation. The objective of this research was to develop a dental material that integrates the following essential properties:
- A coefficient of thermal expansion comparable to that of natural tooth structure
- Strong adhesion to dental tissues
- Long-term color stability
- Insolubility in the oral environment

With continuous advancements in dental material science, the integration of sustainable, high-performance polymers remains a critical focus. Innovations such as epoxy resins have the potential to address previous limitations while enhancing the longevity and effectiveness of dental restorations. As research progresses, the collaboration between material scientists, dental practitioners, and technology developers will be crucial in bridging the gap between scientific innovation and clinical application, ultimately advancing modern dentistry for sustainable and superior patient care (Corrigan et al., 2019).

13. SUMMARY AND FUTURE PERSPECTIVES

The development of bio-based polymers as substitutes for petroleum-based synthetics has gained significant attention due to the non-degradable and non-renewable nature of conventional plastics. Addressing this challenge is crucial, particularly in light of future fossil fuel shortages, which necessitate the exploration and expansion of alternative materials and chemical sources to reduce dependence on fossil-derived resources.

Several promising bio-based polymer alternatives include polyhydroxyalkanoates (PHA), polylactic acid (PLA), starch, protein-based polymers, chitin, chitosan, and polybutylene succinate (PBS).

Categories of Bio-Based Polymers

Bio-based polymers are classified into three main categories based on their source and synthesis method:

1. Natural Polymers from Biomass – These originate from agro-based resources such as starch, cellulose, proteins, chitin, and chitosan.
2. Microbial Polymers – Produced by microorganisms, with PHA being a notable example.
3. Synthetic Biopolymers – Chemically synthesized using monomers derived from agro resources, such as PLA and PBS, both of which are biodegradable.

Although bio-based polymers are still in the early stages of development, continuous research is being conducted to address key challenges, including reducing production costs, improving mechanical properties, and enhancing processing efficiency. Scientists are also exploring ways to introduce functional enhancements such as smart and active packaging applications.

Key Bio-Based Polymers and Their Potential

- PHA (Polyhydroxyalkanoates) – A carbon-neutral and environmentally friendly polymer produced by microorganisms using renewable carbon sources. However, its high production cost remains a barrier to large-scale adoption.
- PLA (Polylactic Acid) – Derived from renewable resources, PLA exhibits high tensile strength and modulus, making it compatible with conventional plastic processing methods.
- Starch-Based Polymers – Compliant with essential biodegradable principles, starch-based materials are particularly suitable for edible coatings and films.
- Chitin and Chitosan – As the most abundant natural amino polysaccharide, chitin is nearly as prevalent as cellulose and has gained significant interest for its versatility and potential applications. Advances in chitin chemistry have expanded its usability in multiple fields.
- PBS (Polybutylene Succinate) – A well-known aliphatic polyester that combines excellent thermomechanical properties, biodegradability, and cost-effectiveness in raw material production.
  The Future of Biodegradable Plastics
  The transition to biodegradable plastics is seen as a vital step toward sustainability, offering multiple benefits:
- Reduction in carbon dioxide and greenhouse gas emissions
- Lower energy consumption during manufacturing
- Decreased plastic waste accumulation
- Opportunities for new industries in biodegradable plastic production

Sustainable **renewable resources** are abundantly available, easy to procure, and cost-effective. They possess **unique natural functionalities**, offering **biodegradability** and serving as **eco-friendly alternatives** to traditional petroleum-based materials. The **modification and enhancement** of these renewable resources have become a key area of research, aiming to introduce **novel properties, improved performance, and environmental sustainability** at competitive costs. With **persistent and extensive research efforts**, sustainable materials have the potential to match, and even surpass, their **petrochemical counterparts**, paving the way for **greener coatings and biomaterials** in the future (Pineva et al., 2024).
In response to the **toxic and inflammatory concerns** associated with synthetic resins, researchers have increasingly focused on **eco-friendly alternatives**. These new-generation resins are being developed to address challenges such as **biocompatibility, safety, and sustainability** while maintaining **high performance and durability**. Among these innovations, the synthesis of **epoxy resins from sustainable materials** has become **a crucial necessity (Cheng et al., 2024)**.
Epoxy-polymer-based composites play a **significant role** in the **rapidly evolving field of biomaterials**, where engineers, scientists, and biologists collaborate to develop advanced materials for **medical and dental applications**. As knowledge and research continue to transform scientific disciplines, **epoxy resins** emerge as **promising candidates** for diverse applications, particularly in **dentistry**. Their **biocompatibility and versatility** allow for modifications that enhance their **mechanical strength, adhesion properties, and long-term stability**, making them **ideal materials for dental restorations and coatings (Bhat et al., 2021)**.
Beyond dentistry, **biocompatible polymers** find applications in **agriculture, medical devices, and engineering technologies**. These materials can be designed to serve as **carriers for reagents, biodegradable components, and structural biomaterials**, contributing to various technological advancements. However, despite their potential, **further research and innovation** are essential to **overcome practical challenges** and **mitigate environmental impacts**. The future of **sustainable biomaterials** lies in **continuous development**, ensuring that they become **viable, high-performance alternatives** to conventional synthetic materials while fostering **eco-friendly and patient-safe solutions (Malik et al., 2024)**.

14. CONCLUSION

This review highlights the various properties of epoxy resins used in dentistry, emphasizing the need for safer alternatives. The development of epoxy resins derived from sustainable resources presents a promising solution to minimize cytotoxicity, particularly during the initial curing stages. The incorporation of vegetable oils (VO) in polymer formulations offers several advantages over conventional synthetic polymers, including renewability, biodegradability, and reduced toxicity. This shift toward sustainable materials not only enhances biocompatibility but also contributes to eco-friendly advancements in dental science. Composite resins, widely used in dental restorations, are synthetic resins, typically acrylic-based, reinforced with a high percentage of ceramic fillers such as glass or silica. These fillers, coated with a coupling agent, enhance their bonding to the resin matrix, improving strength, durability, and aesthetics. This material, commonly referred to as composite, remains a preferred choice for aesthetic and functional restorations in modern dentistry.

REFERENCES

1. Alam, M., Akram, D., Sharmin, E., Zafar, F., & Ahmad, S. (2014). Vegetable oil based eco-friendly coating materials: A review article. *Arabian Journal of Chemistry*, *7*(4), 469-479.
2. Shimada, R., Ohta, Y., & Yokozawa, T. (2024). Synthesis and end-group control of soluble, high-molecular-weight hyperbranched poly (phenylene thienylene) s by non-stoichiometric A2+ B3 Suzuki-Miyaura polycondensation without gelation. *European Polymer Journal*, *214*, 113155.
3. Kireev, M., Korotkov, A., Masharipov, R., Zheltyakova, M., Cherednichenko, D., Gershkovich, V., ... & Chernigovskaya, T. (2022). Suppression of non-selected solutions as a possible brain mechanism for ambiguity resolution in the word fragment task completion task. *Scientific Reports*, *12*(1), 1829.
4. Pham, T. C., Nguyen, V. N., Choi, Y., Lee, S., & Yoon, J. (2021). Recent strategies to develop innovative photosensitizers for enhanced photodynamic therapy. *Chemical reviews*, *121*(21), 13454-13619.
5. Wang, F., Xiang, L., Leung, K. S. Y., Elsner, M., Zhang, Y., Guo, Y., ... & Tiedje, J. M. (2024). Emerging contaminants: a one health perspective. *The Innovation*.
6. Zhao, T., Wang, S., Ouyang, C., Chen, M., Liu, C., Zhang, J., ... & Wang, L. (2024). Artificial intelligence for geoscience: Progress, challenges and perspectives. *The Innovation*.
7. Liu, X., Sathishkumar, K., Zhang, H., Saxena, K. K., Zhang, F., Naraginiti, S., ... & Guo, X. (2024). Frontiers in environmental cleanup: recent advances in remediation of emerging pollutants from soil and water. *Journal of Hazardous Materials Advances*, 100461.
8. Papageorgiou, G. Z. (2018). Thinking green: Sustainable polymers from renewable resources. *Polymers*, *10*(9), 952.
9. Rokaya, D., Srimaneepong, V., Sapkota, J., Qin, J., Siraleartmukul, K., & Siriwongrungson, V. (2018). Polymeric materials and films in dentistry: An overview. *Journal of advanced research*, *14*, 25-34.
10. Davoodi, S., Al-Shargabi, M., Wood, D. A., Rukavishnikov, V. S., & Minaev, K. M. (2024). Synthetic polymers: A review of applications in drilling fluids. *Petroleum Science*, *21*(1), 475-518.

11. Shundo, A., Yamamoto, S., & Tanaka, K. (2022). Network formation and physical properties of epoxy resins for future practical applications. *Jacs Au*, *2*(7), 1522-1542.
12. Chowdhury, A., Singh, S. K., Marker, S., & Anthony, P. (2020). Structural and thermal characterization of synthesized polyester resin based on a new linseed variety (shuats-alsi 2). *Rasayan j. chem*, *13*(03), 1834-1841.
13. Karak, N. (2021). Overview of epoxies and their thermosets. In *Sustainable epoxy thermosets and nanocomposites* (pp. 1-36). American Chemical Society.
14. Shundo, A., Yamamoto, S., & Tanaka, K. (2022). Network formation and physical properties of epoxy resins for future practical applications. *Jacs Au*, *2*(7), 1522-1542.
15. Rath, S., Pradhan, D., Du, H., Mohapatra, S., & Thatoi, H. (2024). Transforming lignin into value-added products: Perspectives on lignin chemistry, lignin-based biocomposites, and pathways for augmenting ligninolytic enzyme production. *Advanced Composites and Hybrid Materials*, *7*(1), 27.
16. Banan, A., Ebadirad, A., & Ebrahimabadi, Y. (2024). Effect of epoxidized liquid CTBN on thermal, mechanical, and rheological properties of epoxy resin. *Organic Chemistry Research*, *10*(1), 13-19.
17. Dzhangurazov, E. B., Petrova, T. V., Shapagin, A. V., Tretyakov, I. V., Korokhin, R. A., Kireynov, A. V., ... & Berlin, A. A. (2025). Fracture Toughness of Winding Carbon Plastics Based on Epoxy Matrices and Reinforced by Polysulfone Film. *Polymers*, *17*(2), 220.
18. Wang, G., Yu, M., Wang, M., Liu, X., Zhang, H., & He, L. (2024). Study of Interlaminar Fracture Toughness and Flexural Properties of Carbon Fibre Composites Reinforced with Polyethersulfone/Graphene Oxide Films. *Composites Communications*, *51*, 102051.
19. Zheng, N., Huang, Y., Liu, H. Y., Gao, J., & Mai, Y. W. (2017). Improvement of interlaminar fracture toughness in carbon fiber/epoxy composites with carbon nanotubes/polysulfone interleaves. *Composites Science and Technology*, *140*, 8-15.
20. Mula, V. R., Ramachandran, A., & Pudukarai Ramasamy, T. (2023). A review on epoxy granite reinforced polymer composites in machine tool structures–Static, dynamic and thermal characteristics. *Polymer Composites*, *44*(4), 2022-2070.
21. Niaki, M. H., Ahangari, M. G., & Pashaian, M. (2022). A material-independent deep learning model to predict the tensile strength of polymer concrete. *Composites Communications*, *36*, 101400.
22. Acordi, J., Borgert, C. H., Peres, F. B., Bochanóski, R., Haltiery, D., Olivo, E. F., ... & Raupp-Pereira, F. (2025). Sustainable Lightweight Artificial Coating Stone Developed with Nepheline Syenite Mining Waste as Filler in Resin Matrix. *JOM*, 1-9.
23. Chen, X. Q., Lin, Y. C., Bai, W. B., Yan, Y. W., & Jian, R. K. (2025). Nonconventional phosphorus-based tertiary amine curing agent enabling the high fire safety, outstanding tensile strength and high glass transition temperature of epoxy resin. *Chemical Engineering Journal*, *505*, 159293.
24. Duraccio, D., Di Maro, M., Vaccaro, F., Faga, M. G., Bartoli, M., Malucelli, G., ... & Gerboni, R. (2025). Improving wear resistance of epoxy resin using bio-oil from hemp biomass: a sound strategy to reduce environmental impact. *Journal of Cleaner Production*, 145003.
25. Patel, P., Bello, D., & Bello, A. (2025). Identifying and Prioritizing Hazardous Chemicals in Construction Metal Structure Coating Systems: A Roadmap for Data-Driven Disease Prevention. *American Journal of Industrial Medicine*, *68*, S23-S44.
26. Santra, G. (2025). Plastic Pollution and One Health Crisis: A Burning Issue in Environmental Medicine. *The Journal of the Association of Physicians of India*, *73*(3), 73-83.
27. Laubach, M., Hildebrand, F., Suresh, S., Wagels, M., Kobbe, P., Gilbert, F., ... & Hutmacher, D. W. (2023). The concept of scaffold-guided bone regeneration for the treatment of long bone defects: current clinical application and future perspective. *Journal of functional biomaterials*, *14*(7), 341.
28. Shome, A., Martinez, I., Pinon, V. D., Moses, J. C., Garren, M., Sapkota, A., ... & Handa, H. (2024). "Reactive" Chemical Strategy to Attain Substrate Independent "Liquid-Like" Omniphobic Solid Anti-Biofouling Coatings. *Advanced Functional Materials*, *34*(36), 2401387.
29. Klingler, W. W., Bifulco, A., Polisi, C., Huang, Z., & Gaan, S. (2023). Recyclable inherently flame-retardant thermosets: Chemistry, properties and applications. *Composites Part B: Engineering*, *258*, 110667.
30. Dinu, R., Lafont, U., Damiano, O., & Mija, A. (2024). Recyclable fully biobased high-performance epoxy thermosets. *Industrial Crops and Products*, *222*, 119645.
31. Satchanska, G., Davidova, S., & Petrov, P. D. (2024). Natural and synthetic polymers for biomedical and environmental applications. *Polymers*, *16*(8), 1159.
32. Riyamol, Gada Chengaiyan, J., Rana, S. S., Ahmad, F., Haque, S., & Capanoglu, E. (2023). Recent advances in the extraction of pectin from various sources and industrial applications. *ACS omega*, *8*(49), 46309-46324.
33. Ribeiro, A. R., Silva, S. S., & Reis, R. L. (2022). Challenges and opportunities on vegetable oils derived systems for biomedical applications. *Biomaterials Advances*, *134*, 112720.
34. Fakhri, V., Janmaleki Dehchani, A., Davoudi, S. A., Tavakoli Dare, M., Jafari, A., Nemati Mahand, S., ... & Khonakdar, H. A. (2024). Advancing biomedical frontiers with functionalized soybean oil: insights into tissue engineering and drug delivery. *Journal of Polymers and the Environment*, 1-28.

35. Silva, V. R., Pinheiro, A. C., Ombredane, A. S., Martins, N. O., Luz, G. V., Carneiro, M. L., & Joanitti, G. A. (2023). Anti-Inflammatory Activity of Pequi Oil (Caryocar brasiliense): A Systematic Review. *Pharmaceuticals*, *17*(1), 11.
36. Saraswat, R., Dhir, A., Balan, A. S. S., Powar, S., & Doddamani, M. (2024). Synthesis and application of sustainable vegetable oil-based polymers in 3D printing. *RSC Sustainability*, *2*(6), 1708-1737
37. Hatton, P. V., Mulligan, S., & Martin, N. (2022). The safety and biocompatibility of direct aesthetic restorative materials. *British Dental Journal*, *232*(9), 611-614.
38. Abraham, A. M., & Venkatesan, S. (2023). A review on application of biomaterials for medical and dental implants. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, *237*(2), 249-273.
39. Zaokari, Y., Persaud, A., & Ibrahim, A. (2020). Biomaterials for adhesion in orthopedic applications: a review. *Engineered Regeneration*, *1*, 51-63.
40. Cho, K., Rajan, G., Farrar, P., Prentice, L., & Prusty, B. G. (2022). Dental resin composites: A review on materials to product realizations. *Composites Part B: Engineering*, *230*, 109495.
41. Adnan, M., Xiao, B., Ali, M. U., Bibi, S., Yu, H., Xiao, P., ... & An, X. (2024). Human inventions and its environmental challenges, especially artificial intelligence: New challenges require new thinking. *Environmental Challenges*, 100976.
42. Pinaeva, L. G., & Noskov, A. S. (2024). Biodegradable biopolymers: Real impact to environment pollution. *Science of The Total Environment*, 174445.
43. Cheng, J., Gao, R., Zhu, Y., & Lin, Q. (2024). Applications of biodegradable materials in food packaging: A review. *Alexandria Engineering Journal*, *91*, 70-83.
44. Bhat, K. M., Rajagopalan, J., Mallikarjunaiah, R., Rao, N. N., & Sharma, A. (2021). *Eco-friendly and biodegradable green composites*. London, UK: IntechOpen.
45. Malik, K., Capareda, S. C., Kamboj, B. R., Malik, S., Singh, K., Arya, S., & Bishnoi, D. K. (2024). Biofuels production: a review on sustainable alternatives to traditional fuels and energy sources. *Fuels*, *5*(2), 157-175.