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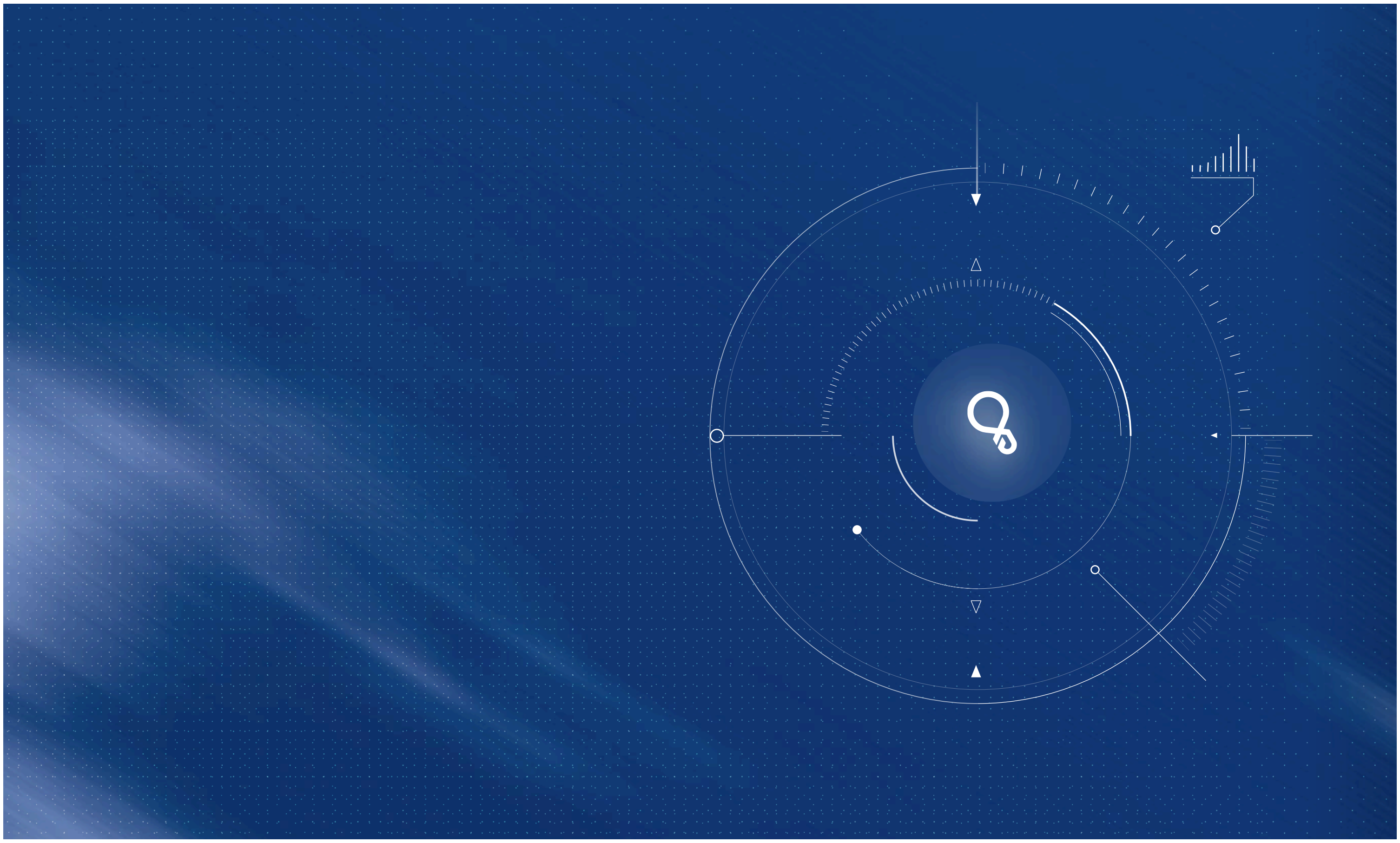

RESEARCH BRIEF

BPA Replacements in Epoxy Resin

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Executive Summary

The intention of this Insight Brief is to provide an analysis of the regulatory and compliance landscape for Bisphenol A (BPA) and its replacements in epoxy resins across North America and Europe, as well as to highlight the latest advancements in BPA-free epoxy resin technologies.

This brief examines current and upcoming regulatory requirements governing BPA and its substitutes, providing insights into compliance challenges and opportunities. It also explores recent innovations in BPA-free epoxy resins, reviewing patents, research, and contributions from key innovators.

Analyst Opinion

Recent developments in BPA-free epoxy resin technology highlight a deepening tension between performance requirements, regulatory mandates, and sustainability imperatives. For instance, the strict deadlines in Europe illustrate a clear policy trajectory: BPA and related bisphenols are increasingly scrutinized for their potential endocrine-disrupting effects, creating an urgent demand for alternatives. In North America, the patchwork of state-level regulations complicates the compliance landscape, yet it also yields opportunities for innovation. Together, these regulatory shifts drive momentum toward bisphenol-free epoxy systems, including a new generation of bio-based monomers, dynamic covalent networks, and high-performance functional resins.

However, the path to large-scale adoption remains challenging. Despite notable progress in bio-based feedstocks, many alternatives still face cost constraints, supply chain variability, and manufacturing hurdles. The most advanced research shows that some formulations can match or exceed BPA in thermal stability, mechanical strength, and even specialized functionalities such as flame retardancy or antibacterial properties. However, integrating these novel materials into established workflows and certification standards (e.g., automotive, aerospace) remains challenging, given issues like high viscosity, dynamic curing profiles, and incomplete data on long-term durability.

In this evolving landscape, an emerging best practice involves formulating hybrid bio-based epoxies. By combining different feedstocks, such as phenolic-based monomers for flame retardancy and vegetable oil-based components for flexibility, researchers can develop alternatives that match or exceed traditional BPA-based resins. This approach often demands sophisticated material design, robust supply chains, and iterative R&D to identify the most synergistic ratios.

While a direct substitute has yet to be found, organizations may benefit more from fundamental reformulations than incremental modifications to the bisphenol backbone. This approach, focusing on novel polymer architectures, dynamic covalent linkages, and end-of-life recovery, prepares materials to meet future regulatory scrutiny and enhance competitive differentiation.

Ultimately, the success of BPA-free epoxy resin technology hinges on a balancing act: meeting exacting mechanical and thermal requirements, conforming to increasingly fragmented regulations, and achieving commercial viability in terms of cost and production scale.

Research Methodology

In our research, we used the Cypris platform, third-party datasets, and broader internet searches to gather relevant data. Additionally, we incorporated secondary sources, including industry articles, company websites, and recent market news. Throughout this process, we refined our approach by adapting our keywords to synonyms and related terms to ensure comprehensive data collection. For our foundational queries, we used Cypris' semantic and Boolean search functionality with the following search terms 'BPA-Free Epoxy Resin' and 'Bio-Based Epoxy Resin', respectively.

Background on BPA

Bisphenol A (BPA) is widely used in epoxy resins due to its ability to impart exceptional mechanical strength, chemical resistance, and thermal stability to the final material. As a core building block in diglycidyl ether of bisphenol A (DGEBA) resins, BPA contributes to the dense, crosslinked network that gives epoxy coatings, adhesives, and composites their durability and performance. These properties make BPA-based epoxy resins essential in applications requiring long-term structural integrity, such as protective coatings for metal packaging, circuit boards, aerospace composites, and industrial adhesives. Furthermore, BPA-based epoxies cure into thermosetting polymers with moderate to high glass transition temperatures, low water absorption, and excellent adhesion, making them ideal for demanding environments where mechanical stress, heat, and chemical exposure are prevalent.

Despite its functional advantages, BPA's widespread use has raised health and environmental concerns, particularly regarding its potential endocrine-disrupting effects. The challenge in replacing BPA lies in maintaining or exceeding the performance characteristics that make it so valuable in epoxy resins. Effective alternatives must balance mechanical strength, thermal stability, chemical resistance, and processability while also addressing regulatory concerns and sustainability goals.[1]

Regulatory and Compliance Landscape

Concerns over BPA's potential endocrine-disrupting effects have led to increased regulatory scrutiny, especially in food-contact materials, childcare products, and consumer goods with frequent human exposure. In response, regulations governing BPA and its alternatives have evolved.

North America

United States

Federal Regulatory Status

Currently, the Food & Drug Administration (FDA) considers BPA safe at the low levels that migrate into food from resin coatings. However, since 2012 it has prohibited BPA-based epoxy resins in baby bottles, sippy cups, and infant formula packaging, after determining that manufacturers had already abandoned those uses. For all other applications, BPA-based materials remain approved.[2] Although the FDA has not introduced more restrictive rules for BPA alternatives, it continues to research and monitor BPA's potential risks, leaving the possibility open for updated regulations should new evidence arise.

State-Level Initiatives

Despite lack of regulations by the federal government, individual municipalities and states have taken

[1] Bisphenol-free and Bio-based epoxy resins
[2] Bisphenol A (BPA): Use in Food Contact Application

action. These state-level regulations have resulted in a fragmented set of requirements for BPA and its alternatives. Notably, California added BPA to its Proposition 65 list of chemicals known to cause reproductive harm in May 2015, mandating warning labels for products containing BPA.[3] The state later expanded health and safety regulations to extend restrictions and replacement guidelines previously specific to BPA to all bisphenols, including Bisphenol S (BPS).[4] Other states, such as Connecticut, Maine, and Washington, have also implemented various regulations on BPA, creating a complex regulatory landscape across the United States.

Canada

Canada currently restricts BPA in products intended for infants, including a ban on polycarbonate baby bottles containing BPA and a phased removal from liquid infant formula packaging.[5] However, the country's current Tolerable Daily Intake (TDI) for BPA remains six times higher than the limit set by the European Food Safety Authority.[6] Health Canada continues to monitor BPA exposure through its Chemicals Management Plan and regularly reviews emerging scientific research.

Mexico

Currently, Mexico does not have specific regulations on the use of Bisphenol A (BPA) or its alternatives.[7]

European Union

Starting in January 2025, the European Union banned BPA in food contact materials (FCMs), including adhesives, rubbers, plastics, varnishes, and coatings, significantly impacting BPA-based epoxy resins. Transitional provisions allow single-use FCMs compliant with previous regulations to remain on the market until July 2026, with exceptions for certain food packaging and professional equipment extending to January 2029. The regulation also extends beyond BPA to include other bisphenols and bisphenol derivatives classified as carcinogenic, mutagenic, toxic to reproduction, or endocrine disruptors.[8] This regulation aims to minimize BPA exposure while ensuring a structured transition for affected industries.

Innovation Snapshot

The following sections explore recent advancements in BPA replacements in epoxy resins, highlighting cutting-edge research and innovative patents that push the boundaries of sustainability, performance, and functionality.

Recent research has made significant strides in moving beyond the use of BPA in epoxy resins by utilizing bio-based feedstocks, such as cardanol, eugenol, vanillin, itaconic acid, resveratrol, and ferulic acid, to enhance mechanical performance and introduce specialized functionalities. Many of these biomass-derived epoxy systems now rival or surpass BPA analogs in strength, thermal stability, and processability. One major area of focus has been the synthesis of flame-retardant epoxy resins, which can be achieved through the incorporation of phosphorus-containing compounds, such as DOPO-based derivatives, cyclotriphosphazenes, and phosphates, or through the use of phosphorus-free strategies, such as rigid and conjugated structures derived from magnolol, resveratrol, and ferulic acid, as well as

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[3] Bisphenol-A Listed as Known to the State of California to Cause Reproductive Toxicity
[4] CA Senate Judiciary Committee
[5] Government of Canada: Bisphenol A
[6] What Does CLARITY-BPA Mean for Canadians?
[7] Challenges to regulate products containing bisphenol A: Implications for policy
[8] Commission Regulation (EU) 2024/3190 of 19 December 2024 on the use of bisphenol A (BPA) and other bisphenols and bisphenol derivatives

heterocyclic structures including Schiff base-modified networks and furan-based epoxy monomers. These approaches improve fire resistance by promoting char formation, radical scavenging, and barrier effects.

Another critical advancement is the preparation of reprocessable, recyclable, or degradable epoxy networks through the incorporation of dynamic covalent bonds, including ester bonds, disulfide bonds, Schiff base structures, Diels–Alder (D-A) addition structures, and acetal structures. These mechanisms enable enhanced material recovery, self-healing capabilities, and end-of-life management, making bio-based epoxy resins more sustainable. Additionally, the design of antibacterial bio-based epoxy resins has gained attention, particularly through the introduction of hydroxyl, Schiff base, and long alkyl chains, which impart antimicrobial properties without compromising mechanical integrity.[9]

Alongside insights into curing reactions and molecular architecture, these advancements are driving the development of high-performance applications, including coatings, composites, and electronics encapsulation. By employing carefully tailored cross-linking strategies and functional moieties, bio-based epoxy resins are achieving closed-loop recyclability, improved fire safety, and antimicrobial functionality while maintaining high-quality material properties. Below is a snapshot of research papers and patents that highlight these advancements.

Research Papers

Title: Versatile levulinic acid-derived dynamic covalent thermosets enabled by in situ generated imine and multiple hydrogen bonds
Publication Date: Jan 01, 2023
Author(s): Yanlin Liu, Zhen Yu, Guangming Lu, Wanding Chen, Zixian Ye, Yueran He, Zhaobin Tang, Jin Zhu
Institution(s): Ningbo Institute of Materials Technology and Engineering
Summary: This research explores the development of bio-based dynamic covalent thermosets using levulinic acid-derived epoxy (ELA) as a sustainable alternative in epoxy resins. The study demonstrates that ELA, cured with 2-(4-aminophenyl)-1H-benzimidazol-5-amine (BIA), forms a robust network through in-situ generated dynamic covalent imine (Schiff base) bonds and multiple hydrogen bonds, resulting in excellent thermal and mechanical properties with T_g up to 165 °C and tensile modulus up to 2422 MPa. The resin exhibits catalyst-free reprocessability, self-repair capability, and intrinsic flame retardancy (LOI of 33.8%, UL-94 V-0 rating), addressing key limitations of traditional thermosets. Additionally, the resin also exhibited 100% antibacterial activity against Escherichia coli and Staphylococcus aureus. This work provides a feasible and simple strategy for the preparation of high-performance and versatile bio-based dynamic covalent thermosets.
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Title: Recyclable flame retardant phosphonated epoxy based thermosets enabled via a reactive approach
Publication Date: Apr 20, 2023

[9] Recent Development of Functional Bio-Based Epoxy Resins

Author(s): Wenyu Wu, Valentin Rougier, Zhenyu Huang, Dambarudhar Parida, Sandro Lehner, Andri Casutt, Daniel Rentsch, Karin Brändli Hedlund, Gion Andrea Barandun, Véronique Michaud, Sabyasachi Gaan
Institution(s): Empa Swiss Federal Laboratories for Materials Science and Technology
Summary: This research paper presents the development of a novel phosphonated epoxy-based thermoset with inherent flame retardancy, recyclability, and reprocessability. By incorporating reactive phosphonate esters into the epoxy network, the material exhibits high thermal stability, reduced flammability, and the ability to be reshaped or repaired through transesterification-driven dynamic bond exchange. The study demonstrates that a phosphorus content of 2.5% significantly enhances fire resistance, reducing the peak heat release rate by 75% and smoke production by 72.5%, while a higher phosphorus content (6%) was necessary for damage reparability after scratching, reprocessability and also recyclability. These phosphonated thermosets' ability to maintain structural integrity while being recyclable positions them as a promising BPA-free epoxy resin alternative in circular economy applications.
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Title: Recyclable epoxy resins with different silyl ether structures: structure-property relationships and applications in diverse functional composites
Publication Date: Apr 01, 2024
Author(s): Yinqiao Liu, Mengna Wu, Quan Wen, Ling Zhang, Qiuran Jiang, Jun Wang, Wanshuang Liu
Institution(s): Shanghai High Performance Fibers and Composites Center
Summary: This research introduces three cycloaliphatic epoxy monomers containing silyl ether linkages (CESI1, CESI2, CESI3) that form thermoset networks with high glass transition temperatures, good mechanical strength, and notably low viscosity, qualities valued in epoxy formulations traditionally reliant on BPA. While not strict "drop-in" replacements, these BPA-free epoxies offer a competitive alternative by delivering similarly robust performance and processing characteristics, coupled with the added benefit of chemical degradability for potential filler recovery. This contrasts with standard BPA-based epoxies, which are challenging to recycle. By demonstrating that the network's crosslink density, thermal stability, and mechanical properties can be tuned through different phenyl substitutions, and that the cured resins are reprocessable, the study shows how these silyl ether–based monomers could feasibly supplant BPA in applications demanding both high performance and improved recyclability.
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Title: Towards sustainable and recyclable plastic materials: Vanilin-based epoxy bio-composites with spruce bark powder and hydrochar, pioneering green chemistry solutions for shape memory applications
Publication Date: Aug 01, 2024
Author(s): Roxana Dinu, Iuliana Bejenari, Irina Volf, Alice Mija
Institution(s): University Côte d'Azur
Summary: In this study, a novel approach to developing sustainable and recyclable materials sourced from lignocellulosic biomass is introduced. This paper details an epoxy-based resin using diglycidyl ether of vanillin (DGEVA) for curing with dodecenylsuccinic anhydride (DDSA), in presence of significant proportions of either spruce bark powder or its hydrochar. The resulting bio-based thermosets exhibit impressive thermomechanical performance, as evidenced by an increased storage modulus (from 1.5 GPa to 3.1 GPa) when hydrochar is incorporated, and minimal changes in thermal stability and glass

transition temperature. Coupled with straightforward mechanical and chemical recycling methods, including alkaline and mild-alcoholysis processes, these materials show strong potential for circular uses. Importantly, these DGEVA/DDSA-based materials retain the key mechanical strength, thermal stability, and processability typically demanded of BPA-based epoxy resin formulations, thereby making them suitable for a range of industrial applications without the trade-offs often associated with bio-derived alternatives.

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Patents

Title: Decomposable and recyclable epoxy thermosetting resins
Publication Number: US-11891473-B2
Publication Date: Feb 5, 2024
Assignee: The Regents of The University of California
Summary: This patent outlines a new type of thermoset precursor composition that could enhance material properties for various applications. The authors created a backbone structure using imine bonds to connect aromatic compounds and aliphatic chains, incorporating either epoxy or aldehyde groups at the ends. Through their methods, they discovered that the composition could feature multiple combinations of these functional groups, which may improve the performance and versatility of thermoset materials. The significance of this study lies in its potential to advance the field of polymer science, offering new materials that could be used in industries ranging from electronics to construction.

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Title: Bio-based resin, curable composition and polyurethane based thereon, and related methods
Publication Number: WO-2023034101-A1
Publication Date: Mar 8, 2023
Applicants: Ingevity South Carolina
Summary: This patent describes novel bio-based epoxy resins obtained by reacting tall oil- or plant oil-derived fatty and rosin acids with glycidyl ether components that have at least two epoxide groups. The resulting functionalized “bio-based” resins can be blended with other epoxy resins or used alone to form coatings, adhesives, and composites with enhanced mechanical strength, thermal stability, hydrophobicity, and flexibility. In addition, these bio-based resins can be converted into polyurethane polymers (by reacting with isocyanates) to produce materials with adjustable properties, such as higher glass transition temperatures, toughness, and water resistance, while incorporating a significant percentage of renewable content from natural feedstocks.

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Title: Furanic diglycidyl ethers and esters and use thereof
Publication Number: WO-2022261739-A1
Publication Date: Dec 21, 2022
Applicants: Braskem S.A.
Summary: The patent describes novel furanic diglycidyl ethers and esters, which serve as key components in the formulation of epoxy resins. These compounds are derived from renewable sources and offer enhanced performance characteristics, such as improved mechanical strength, thermal stability, and chemical resistance. The invention details the synthesis methods for these furanic-based

compounds and their application in epoxy resin formulations, making them suitable for various industrial applications, including coatings, adhesives, and composites. The patent highlights their potential as sustainable and high-performance alternatives to traditional petroleum-based epoxy resins.
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Title: Glycerol-based epoxy resins
Publication Number: US-11859079-B2
Publication Date: Jan 1, 2024
Assignees: Steed Mifsud Pty Ltd
Summary: This patent describes a novel composition and method for producing epoxy resins using glycerol as a key component. The invention aims to provide an environmentally friendly and sustainable alternative to traditional petroleum-based epoxy resins by utilizing bio-based feedstocks. The patent outlines the synthesis process, material properties, and potential applications of these resins, emphasizing their suitability for coatings, adhesives, and composites. By leveraging glycerol's renewable nature, the invention contributes to reducing dependence on fossil fuels while maintaining or improving the mechanical and thermal properties of conventional epoxy materials.
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Notable Entities

The following section profiles leading innovators, including companies, research institutions, and individuals, advancing the development of BPA-free epoxy resins. Analysis of patent activity indicates a significant concentration of research and development efforts from Chinese organizations.

For instance, a Boolean search for "bio-based epoxy resins" over the past 10 years reveals that the top three patent holders collectively account for 159 patents, representing approximately 8.2% of the 1,928 total patents in this field. The table below outlines the top contributors:

Patent Holder	Number of patents
Ningbo Institute of Materials Technology & Engineering	63
Nanjing Tech University	61
Jiangnan University	35

While these contributions are substantial, this section highlights a broader range of innovators to present a more globally representative perspective.

Empa - Swiss Federal Laboratories for Materials Science and Technology

Empa is a Swiss research institution that conducts materials and technology research. Its research teams have made significant contributions to the development of sustainable alternatives to BPA-based epoxy resins. In 2023, Empa researchers created an epoxy resin[10] that can be both repaired and recycled, addressing the longstanding challenge of recycling traditional epoxy resins. This work is particularly relevant for industries using fiber-reinforced polymers, such as aerospace, automotive, and renewable energy sectors. Empa's work not only aims to replace BPA but also to improve the environmental footprint of carbon fiber production and potentially reduce costs.

Ingevity

Ingevity is an organization that provides specialty chemicals, high-performance carbon materials and engineered polymers. The company has leveraged its expertise as a bio-based raw materials supplier to create a series of renewable monomers under the tradename AltaMer[11]. These products are derived from rosin, a natural resin found in trees, which is isolated during the paper pulping process and purified in Ingevity's biorefineries. The company has also developed biobased epoxy resins derived from distilled tall oil (DTO), which offer performance benefits and environmental advantages.[12]

Institute of Chemistry of Nice

The Institute of Chemistry of Nice in the University Côte d'Azur has contributed to developing sustainable BPA replacements in epoxy resins. Researchers have successfully created 100% biobased epoxy resins suitable for space applications and explored novel polymers using limonene and Schiff-based thermosets derived from vanillin or syringaldehyde. These alternatives offer superior material properties, high mechanical strength, and eco-friendly characteristics, making them promising candidates for various industries seeking sustainable materials.

Prof. Zhu Jin

Prof. Zhu Jin is the Head of the Institute of Materials Technology at the Ningbo Institute of Material Technology and Engineering, Chinese Academy of Sciences. Dr. Zhu got his Ph.D. at Marquette University and his postdoctoral study at Cornell University. He has published over 600 academic papers and has expertise on bio-based polymers, flame retardant materials, and functional nanocomposites. Prof Zhu Jin was the Principal Investigator of the team that prepared a bio-based epoxy resin with a balance of fast self-healing, good shape memory, easy reprocessing, mild degradation, bacterial resistance, and good mechanical properties.[13]

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[10] Recyclable flame retardant phosphonated epoxy based thermosets enabled via a reactive approach
[11] Ingevity's AltaMer™—renewable monomers and oligomers
[12] Ingevity - CoatingsTech
[13] Versatile levulinic acid-derived dynamic covalent thermosets enabled by in situ generated imine and multiple hydrogen bonds

- [LinkedIn]

Material Analysis

Choosing the right bio-based epoxy system requires balancing performance, cost, and processing challenges. The table below summarizes key materials, with detailed information provided immediately after.[14] [15]

Material	Source	Key Advantages	Key Challenges	Best-Suited Applications
Lignin-Derived Epoxies	Byproduct of paper & biorefinery industries	High char yield, effective flame retardancy, good adhesion with natural fibers	High viscosity, inconsistent molecular weight, lower thermal stability vs. BPA-based epoxies	Flame-retardant composites, adhesives, coatings, electrical insulation
Cardanol-Derived Epoxies	Cashew nutshell liquid	Balance of rigidity & flexibility	Inconsistent composition, complex epoxidation, high production cost	Coatings, adhesives, flexible thermosets
Eugenol-Derived Epoxies	Cloves and cinnamon	Antibacterial, flame retardant, tunable mechanical performance	Limited industrial availability, competing uses, complex curing mechanisms	Flame-retardant materials, antibacterial coatings, adhesives
Vanillin-Based Epoxy Resins	Derived from lignin	High crosslink density, flame retardancy	High production costs, limited supply, specialized curing agents needed	Coatings, adhesives, vitrimers, structural composites (when reinforced)
Furan-Based Epoxy Systems	Agricultural waste (corn cobs, bagasse)	High thermal stability, rigidity, chemical degradation resistance	Brittleness, complex synthesis processes	Low volatile organic compound coatings, adhesives with enhanced properties
Rosin- and Tannic Acid-Based Epoxies	Pine resin & plant polyphenols	Flame retardant, good fiber adhesion	Brittleness, source-dependent variability, limited structural applications	Coatings, wood adhesives, vitrimers, flame-retardant materials
Vegetable Oil-Based Epoxy Systems	Soybean, linseed, castor oil	Low viscosity, cost-effective, flexible, good adhesion & chemical resistance	Low mechanical strength, low glass transition temperature	Coatings, paints, reactive diluents, adhesives
Multi-Component Bio-Based Systems and Hybridization	Combination of multiple bio-based epoxies	Enhances performance & processing in single source materials	Ensuring component compatibility, balancing performance trade-offs	Self-healing materials, high-performance composites, flexible thermosets

[14] Use of bio-epoxies and their effect on the performance of polymer composites: a critical review
[15] Recent Development of Functional Bio-Based Epoxy Resins

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Phenolic-Based Epoxy Systems (lignin, cardanol, eugenol)

Phenolic-based epoxies represent a diverse class of bio-based alternatives derived from plant sources. These systems share a common aromatic polyphenol structure, which enhances flame retardancy and mechanical performance, but they differ in processing challenges and flexibility.

Lignin-Derived Epoxies

Lignin, a byproduct of the paper and biorefinery industries, offers an abundant and sustainable feedstock for bio-based epoxies. Its high char yield makes it an effective flame-retardant epoxy alternative, and its good adhesion with natural fibers enhances composite applications. However, high viscosity, inconsistent molecular weight distribution, and lower thermal stability compared to BPA-based epoxies limit its scalability. Developing standardized fractionation and chemical modifications will be essential for broader adoption.

Cardanol-Derived Epoxies

Cardanol, extracted from cashew nutshell liquid (CNSL), provides a unique balance of rigidity and flexibility due to its phenolic ring and long aliphatic side chain. This makes it suitable for coatings, adhesives, and flexible thermosets. However, raw cardanol's inconsistent composition, complex epoxidation process, and relatively high production cost pose adoption challenges. Ensuring consistent quality control and cost-effective processing techniques is crucial for expanding its market potential.

Eugenol-Derived Epoxies

Eugenol, obtained from cloves and cinnamon, presents antibacterial properties, natural flame retardancy, and tunable mechanical performance. These properties make it attractive for specialized flame-retardant and high-performance applications. However, eugenol suffers from limited industrial availability, competing uses in the pharmaceutical and fragrance industries, and complex curing mechanisms. Future research could focus on scaling up production and optimizing curing methods to expand its application in commercial epoxy formulations.

Vanillin-Based Epoxy Resins (Advanced Lignin-Derived System)

Vanillin, a refined derivative of lignin, offers an aromatic alternative to BPA with high crosslink density, flame retardancy, and potential for vitrimer applications. Its high-performance properties make it suitable for structural and reprocessable epoxy systems. However, high production costs, limited supply, and the need for specialized curing agents hinder widespread adoption. Scaling up oxidation processes and reducing production costs will be critical to its long-term feasibility.

Furan-Based Epoxy Systems

Furan-derived epoxies, obtained from agricultural waste (e.g., corn cobs, bagasse), provide high thermal stability, rigidity, and resistance to chemical degradation. Their heterocyclic structure differentiates them from benzene-based phenolic systems. However, brittleness and complex synthesis processes limit their current adoption. Advances in curing chemistry and flexibility-enhancing modifications are needed to make furan-based epoxies more viable in structural applications.

Rosin- and Tannic Acid-Based Epoxies

Rosin (pine resin) and tannic acid (from plant polyphenols) contribute to flame-retardant, bio-based epoxy systems with good fiber adhesion. They are commonly used in coatings and adhesives rather than structural applications due to their brittleness and source-dependent variability. Industrial purification and modification processes must be improved to expand their applications in commercial bio-composite systems.

Vegetable Oil-Based Epoxy Systems

Vegetable oils such as soybean, linseed, and castor oil provide low-viscosity, cost-effective epoxy alternatives. Their flexibility, adhesion, and chemical resistance make them valuable for coatings and reactive diluents. However, their low mechanical strength and glass transition temperatures limit standalone use in structural applications. Hybrid formulations with more rigid bio-resins are necessary to improve their performance in demanding applications.

Multi-Component Bio-Based Systems and Hybridization

Hybridization, combining different bio-based epoxies, is a promising strategy to enhance performance and processing characteristics. Blending phenolic-based epoxies (e.g., lignin, eugenol, cardanol) with vegetable oil-based epoxies improves flexibility while maintaining flame retardancy. However, ensuring component compatibility and balancing performance trade-offs remain key challenges. Future development could focus on developing synergistic formulations that maximize bio-content while preserving high mechanical and thermal stability.

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