Epoxy Resin Recycling: Challenges, Technologies, and the Path to Sustainable Circularity

Rumana Hossain[a]*, Brett Watson[b] and Veena Sahajwalla[a]

[a]Centre for Sustainable Materials Research & Technology, SMaRT@UNSW, UNSW SYDNEY, Australia
[b]Siemens Ltd., Smart Infrastructure, Electrification and Automation, QLD 4207, Australia

*Corresponding Author: r.hossain@unsw.edu.au

Abstract

Epoxy resins are critical in engineering due to their superior mechanical, thermal, and chemical properties, yet their crosslinked structure poses major recycling challenges. This review presents a comprehensive synthesis of emerging strategies for epoxy resin sustainability, uniting advanced recycling methods, bio-based material innovations, and life cycle assessments (LCA) with patent and policy analyses. It critically evaluates chemical, thermal, mechanical, and hybrid recycling techniques, emphasising scalability, cost-effectiveness, and environmental performance. Key developments include solvolysis-based depolymerisation, vitrimer chemistry, and ionic liquid-assisted degradation, enabling high-purity monomer recovery and fibre preservation. The integration of bio-based epoxies—derived from lignin, vanillin, and plant oils—is explored alongside dynamic covalent bonding systems to create fully reprocessable thermosets. LCA results indicate carbon footprint reductions of up to 39% for these alternatives, affirming their industrial potential in aerospace, automotive, and electronics. A thorough patent landscape analysis highlights a growing shift toward chemical recycling and circular resin design. This review bridges fundamental chemistry with applied innovation, identifying knowledge gaps, benchmarking current solutions, and outlining scalable pathways for implementation. By aligning technological advances with policy and market trends, it offers critical insights for accelerating the transition to circular, sustainable epoxy resin systems.

Keywords: Epoxy resin recycling, circular economy, solvolysis, vitrimer chemistry, ionic liquid depolymerisation, bio-based epoxy, dynamic covalent bonding, life cycle assessment (LCA), patent landscape analysis, scalability in waste management.

Impact statement:

Epoxy resins are essential to wind turbines, vehicles, aircraft, buildings and electronic systems because they are strong and durable. However, these same properties make cured epoxy difficult to repair, reshape or recycle. Growing volumes of epoxy-containing waste therefore

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10.1017/S2978168X26000040

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https://doi.org/10.1017/S2978168X26000040 Published online by Cambridge University Press

create global challenges through landfill dependence, loss of valuable materials, continued demand for fossil-based raw materials and avoidable greenhouse-gas emissions.

This review brings together evidence on mechanical, thermal, chemical and emerging hybrid recycling methods, alongside bio-based resins, repairable and reprocessable resin designs, life-cycle performance, patents and policy. It shows that no single solution suits every product or waste stream. Mechanical recycling uses relatively little energy but often produces lower-value materials. Thermal and chemical processes can recover valuable fibres and chemicals, although they may require substantial energy, solvents, catalysts and emission controls. Reviewed life-cycle evidence indicates carbon footprint reductions of up to 39% for selected bio-based alternatives, while new reversible or cleavable resin networks can enable repair, reuse and controlled separation at end of life.

The wider benefit of this work is a practical basis for choosing recycling and material-design strategies that retain product value, reduce waste and emissions, and support a circular economy without sacrificing engineering performance. It also cautions that renewable content alone does not guarantee recyclability or biodegradability.

Successful implementation will require more than laboratory advances. Technologies must be demonstrated at pilot and industrial scales using representative waste streams, with reliable collection and sorting, solvent and catalyst recovery, safe emissions management, consistent recovered-material quality, credible costs and transparent life-cycle assessment. Clear design-for-recycling standards, supportive policy, and collaboration among material producers, manufacturers, users and recyclers will be essential. By identifying these priorities, the review helps direct research, investment and industrial action towards safe, scalable and economically viable circular epoxy systems.

Introduction

Epoxy resins are indispensable materials in modern industries, valued for their exceptional mechanical strength, chemical resistance, and thermal stability. These thermosetting polymers are used as thin layers in coatings and adhesives [1, 2] and as bulk materials in construction, automotive, energy, and other engineering applications [3, 4]. However, the tightly crosslinked molecular structure that provides this performance [5] also makes cured epoxy difficult to recycle. This creates substantial end-of-life (EoL) challenges and conflicts with circular-economy objectives. Importantly, the widely cited projection of approximately 12,000 million tonnes (12,000 Mt) by 2050 refers to cumulative global plastic waste expected to accumulate in landfills or the natural environment if prevailing trends continue; it is not a projection of epoxy waste [6]. Comparable global epoxy-specific waste generation and recycling statistics are not yet consistently reported. The development of reliable, scalable recycling technologies for epoxy resins therefore remains a critical research and industrial priority.

The recycling of epoxy resins is particularly challenging because, unlike thermoplastics, they cannot be remelted or reshaped after curing [5], due to their permanent three-dimensional network. Traditional disposal methods, such as landfilling and incineration, not only result in the loss of valuable resources but also contribute to environmental degradation through greenhouse gas emissions and pollution [7]. To address these challenges, various recycling techniques have been developed or are under research, including mechanical recycling [8], chemical recycling (like solvolysis and pyrolysis) [9], and thermal recovery processes [10]. Emerging approaches such as dynamic covalent bonding [11], and bio-based epoxy formulations [12], are also being explored to enhance recyclability while maintaining the material's high-performance properties.

https://doi.org/10.1017/S2978168X26000040 Published online by Cambridge University Press

Globally, significant strides have been made in developing advanced recycling technologies for epoxy resins, aligning with frameworks like the United Nations Sustainable Development Goal 12 (Responsible Consumption and Production) and the European Union's Circular Economy Action Plan [13, 14]. Chemical recycling methods like solvolysis use solvents to break down the resin matrix into reusable components while recovering valuable fillers such as carbon or glass fibres from composite materials [9]. In addition, bio-based epoxy resins derived from renewable resources such as vegetable oils and lignin are gaining attention. These materials not only reduce dependencies on fossil fuels but also improve recyclability through tailored chemical structures. Innovations like dynamic covalent bonding systems allow for reversible crosslinking, enabling repair and reuse of epoxy networks while retaining their mechanical properties.

In Australia, the push toward sustainable material management is gaining momentum in alignment with national goals such as doubling circularity by 2035 [15]. Policies like the plastic waste export ban (2021) and the target of recycling 70% of plastic packaging by 2025 reflect the country's commitment to reducing waste and fostering innovations in recycling technologies [16]. However, when it comes to thermoset materials like epoxy resins, Australia is still in the early stages of adopting advanced recycling solutions [15], despite the growing waste from applications like wind turbine blades and marine coatings. Local companies are beginning to explore sustainable alternatives to traditional epoxy resin. For instance, Change Climate Pty Ltd offers bio-based epoxy resins made from renewable resources that align with global trends toward greener materials [17]. Similarly, Sanded Australia has introduced Surfset Eco Bio Carbon Epoxy Resin, which incorporates up to 34% recycled content to minimise its environmental impact [18]. These initiatives highlight the potential for Australian industries to contribute to global advancements in recyclable epoxy technologies while addressing domestic waste management challenges.

The challenges associated with recycling epoxy resins are multifaceted. Mechanical recycling often results in low-value fillers rather than high-performance materials suitable for demanding applications [7]. Chemical recycling methods can be energy-intensive and costly, limiting their commercial viability at scale [7, 9]. Additionally, the lack of standardization in recycling processes poses a barrier to widespread adoption across industries [19]. On the other hand, opportunities abound as global demand for sustainable materials continues to rise. The growing emphasis on renewable energy sources like wind power has increased interest in recyclable composites for turbine blades, which heavily relies on epoxy resins and has projected contribution to an estimated 2.9 million tonne by 2050 of composite waste annually [20]. This report explores the fundamental chemistry, current and emerging recycling technologies, bio-based innovations, and policy implications to chart a path toward sustainable circularity for these critical materials.

The transition towards a circular economy for epoxy resins requires a comprehensive understanding of material production, industrial applications, end-of-life challenges, and emerging recycling pathways. Figure 1 provides an overview of the epoxy resin life cycle, illustrating the flow from conventional and bio-based feedstocks through manufacturing and application stages to end-of-life management. It also highlights key recycling technologies, including mechanical, thermal, chemical,

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and dynamic covalent/vitrimer-based approaches, and their role in enabling material recovery and closed-loop reuse.

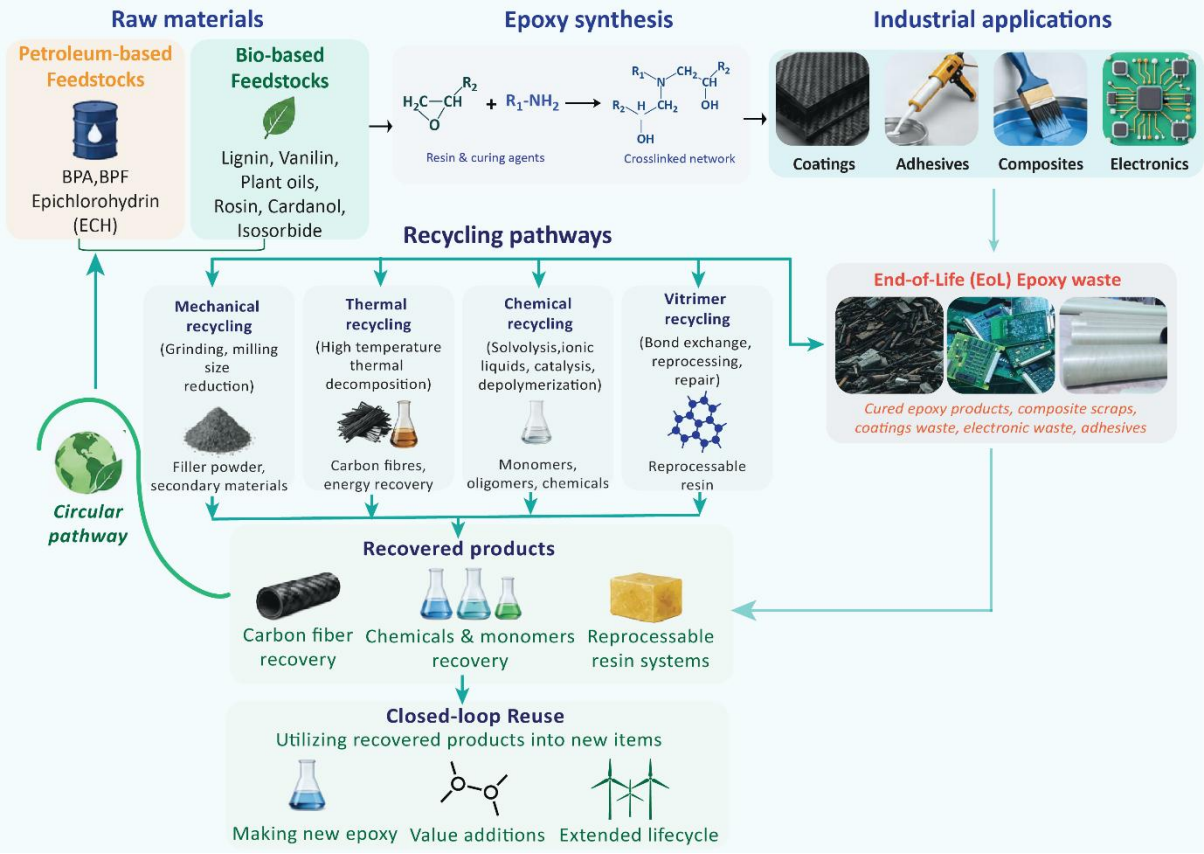


Figure 1. The epoxy resin life cycle and circular economy pathways. The figure illustrates the progression from petroleum-based and bio-based feedstocks to epoxy synthesis and industrial applications, followed by end-of-life waste generation. Recycling routes including mechanical recycling, thermal recycling (pyrolysis), chemical recycling (solvolysis and ionic-liquid-assisted depolymerisation), and dynamic covalent/vitrimer recycling are highlighted, demonstrating pathways for recovering fibres, monomers, chemicals, and reprocessable resin systems to support closed-loop material reuse and sustainable circularity.

Fundamentals of Epoxy Resins

Chemical Structure and Crosslinking

Understanding the chemical structure and behaviour of epoxy resins is fundamental to addressing their recycling challenges, as their inherent properties directly impact the feasibility of sustainable EoL management. Epoxy resins are a class of thermosetting polymers characterised by the presence of reactive epoxy groups, which undergo crosslinking reactions with curing agents to form rigid, three-dimensional networks. This highly crosslinked structure provides exceptional mechanical strength, chemical resistance, thermal stability, and electrical insulation properties. Epoxy resins derive their functionality from the presence of reactive epoxide groups (three-membered cyclic ethers), which enable crosslinking through polymerisation with curing agents [21]. The molecular structure of epoxy resins varies based on their backbone composition. Glycidyl based epoxies, such as bisphenol-A (BPA) and bisphenol-F (BPF), feature aromatic backbones with terminal glycidyl ether groups [21]. These aromatic structures confer high rigidity, thermal stability and chemical resistance, making them ideal for structural applications [5]. In contrast, cycloaliphatic epoxies incorporate non-aromatic rings,

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reducing viscosity and enhancing UV resistance, which is critical for outdoor coatings and electronics [5, 21]. This irreversible crosslinking, while advantageous for durability, poses significant barriers to recycling, as it prevents remelting or reshaping unlike thermoplastics, necessitating advanced recovery methods.

Curing Mechanisms

The curing mechanism involves nucleophilic attack on the strained epoxide ring by active hydrogen donors (e.g. amines and anhydrides) [5], initiating a step-growth or chain-growth polymerisation. For example, aliphatic amines react with epoxide groups to form secondary amines and hydroxyl intermediates, which further propagate crosslinking [22]. The curing process is influenced by the type of curing agent and temperature conditions. Amine-based agents (e.g. aliphatic polyamines) enable room-temperature curing but yield lower crosslink density, while anhydrides or aromatic amines require elevated temperatures to achieve dense, thermally stable networks [22]. Studies reveal that two-stage curing (pre-curing at low temperatures followed by post-curing at higher temperatures) enhances crosslink density and glass transition temperature, compared to single-stage high-temperature curing [21]. For instance, Chiao (1990) demonstrated that curing tetraglycidyl-4,4'-diaminodiphenylmethane with 4,4'diaminodiphenyl sulfone produces a highly crosslinked network with superior mechanical properties due to optimised reaction kinetics [23]. The resulting three dimensional networks governs mechanical strength and chemical resistance with higher crosslink density correlating to rigidity and thermal stability but reduced fracture toughness [22]. This dense network, while critical for performance, complicates recycling efforts, often requiring a chemical or thermal breakdown to recover valuable components.

Stoichiometric Relations and Curing Kinetics

The stoichiometric ratio between epoxy groups and the functional groups of the curing agent is crucial for achieving optimal crosslinking. For instance, in amine-cured epoxy systems, each epoxy group ideally reacts with one active hydrogen from the amine [24]. Deviations from the ideal stoichiometric ratio can lead to unreacted epoxy groups or curing agent molecules, resulting in incomplete curing and compromised mechanical properties [24, 25]. Excess epoxy groups may lead to a more brittle material, while excess curing agent can plasticize the matrix, reducing its strength and thermal stability [24]. The stoichiometry is influenced by the epoxy equivalent weight (EEW) of the resin and the amine hydrogen equivalent weight (AHEW) of the curing agent. These values are used to calculate the correct mix ratio to ensure proper curing [26, 27].

$$Resin\ Weight/Curing\ Agent\ Weight\ = \frac{EEW\ \times\ n_{resin}}{AHEW\ \times\ n_{curing\ agent}}$$

Where, n_{resin} = number of epoxy groups per molecule

$n_{curing\ agent}$ = number of active sites (such as amine hydrogens or carboxyl group) per molecule that can react with epoxy groups

The curing process involves complex kinetics that determine the rate of crosslinking and the development of the thermoset network. The reaction rate is influenced by several factors, including temperature, reactant concentrations, and the presence of catalysts or accelerators [27]. Initially, the reaction may proceed slowly due to low mobility of reactants, but as the temperature increases, the reaction rate accelerates. However, as the network forms, mobility decreases, eventually leading to diffusion-controlled kinetics [27]. Gelation and vitrification are two critical transitions during curing. Gelation is the point at which the liquid resin transforms into an infinite network, resulting in a gel-

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like state [28]. Vitrification occurs when the glass transition temperature of the reacting mixture rises to the curing temperature, causing the reaction to slow down significantly or stop entirely [28]. To achieve full cure, it may be necessary to increase the temperature to allow the reaction to proceed further. Understanding these curing dynamics is key to designing epoxy systems that balance performance with potential recyclability, such as through reversible curing agents or dynamic bonding innovations.

Their versatility to alter the molecular structure to adapt to different properties and formulation, creates a diverse array of epoxy resin types suited for applications in aerospace, automotive, electronics, construction and coatings. The principal epoxy resin types and their applications are summarised in Table 1.

Table 1. Types of Epoxy Resin [22, 29, 30]

Type	Molecular Structure	Key Features	Applications
Bisphenol-A	Contains aromatic rings from BPA and glycidyl ether groups, forming a rigid and strong network upon curing	Most common type, with high mechanical strength and chemical resistance	Coatings, adhesives, civil engineering materials and electrical insulation
Bisphenol-F	Similar to BPA but with few methyl groups, resulting in lower viscosity and higher crosslinking potential	Lower viscosity than BPA with enhanced thermal and chemical resistance	High performance coatings, adhesives, and composites
Epoxy phenol novolac	Derived from phenolic novolac prepolymers with multiple epoxy groups per molecule, enabling dense crosslinked networks	High crosslinking density	Aerospace composites. High temperature coatings and in harsh chemical environments
Cycloaliphatic	Features cycloaliphatic rings providing enhanced UV stability	Excellent UV resistance and dielectric properties	Electrical components (insulators), automotive electronics and outdoor coatings
Halogenated	Bromine or fluorine present in molecular structure for flame retardancy	Flame retardant properties	Electrical Insulation, electronic devices, PCBs
Aliphatic	Composed of aliphatic alcohols or acids, resulting in flexible chains with lower rigidity than aromatic resins	Low viscosity and improved adhesion	Reactive diluents, adhesives, flexible substrate coating
Multifunctional Epoxy	Contains multiple epoxy groups	Higher crosslinked density	Aerospace composites, structural adhesives
Bio-based Epoxy	Contains bioderived components like lignin or vegetable oils	Derived from renewable resources	Ecofriendly coating, adhesives and composites

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Applications of Epoxy Resins in Industry

Epoxy resins are widely recognised for their versatility as thermosetting polymers, finding extensive use across multiple industries due to their superior mechanical strength, chemical resistance, thermal stability, and excellent adhesion. Their application ranges from coatings and adhesives to composites, electronics, construction, and specialised formulations incorporating additives like carbon fibres and silica dust.

Thin Films

Pre-catalysed epoxy resin films are used extensively in aerospace and electronics for their easy handling and uniform thickness. Often based on Bisphenol-A Diglycidyl Ether (DGEBA) for strong adhesion, these films ensure consistent bonding under heat and pressure, eliminating variations in adhesive distribution [31]. They are critical for bonding composite materials (composite-to-composite, composite-to-honeycomb, composite-to-metal) in aircraft structures and for protecting electronics components from environmental factors, as well as serving as anti-static materials with conductive coatings like graphene/carbon nanowires (GN/CNWs) [32]. Additionally, they are studied for dynamic surface fluctuations during curing, which impacts their use in coating materials and insulator films [31]. They are also used in applications like cholesteric liquid crystal films with microcracks for specialised optical properties [33], and in resin art for decorative surfaces due to their precise application capabilities, with mechanical and dielectric properties confirmed through studies on tensile strength and dielectric constants [34].

Adhesives

Epoxy resin adhesives are renowned for their strong bonding capabilities, often categorised as structural or engineering adhesives, and are available in various forms with specific resin types like DGEBA for general use. They are used across industrial, construction, and consumer sectors for their high-bonding strength (up to 2000 psi) and resistance to physical and chemical influences [35]. Recent advancements include toughened adhesives using polystyrene-b-polyisoprene-b-polystyrene (SIS) and hydrogen-bonded SIS (h-SIS), significantly enhancing peel and impact strengths (up to 22 times higher than neat epoxy) for applications in automotive weight reduction and sustainability [35]. They are available as:

a. **Liquid Adhesives:** Typical two component systems requiring mixing with a hardener, often using BPA based low viscosity epoxy resins for fast wet out. They are ideal for bonding diverse surface like wood, metals, plastics, and ceramics in automotive assembly, consumer repairs and construction applications such as the tile installation, with robust adhesion properties [35].
b. **Pastes or Gels:** Often one component systems based on DGEBA, curing at elevated temperatures of 120°C to 175°C. These are used for fillings and sealing gaps, especially between metal surfaces in industrial bonding (aircraft parts, sports equipment) and quick repairs in construction, leveraging their high mechanical strength [35].
c. **Tapes or Films**: Also known as structural adhesive tapes, these are pre-formed epoxy adhesives, providing uniform application in aerospace for bonding aircraft components and in electronics for securing delicate parts, with enhanced toughness from SIS modifications as potential future applications [35].

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Composites

Epoxy resin is used as a binding agent to enhance strength, durability, and resistance in demanding environments, often using DGEBA based epoxy resins for their robust adhesive properties [35]. These composites are widely used in aerospace, automotive, wind energy, marine construction, and sports equipment for their high-performance characteristics. They are typically available in:

a. **Epoxy-impregnated fibre sheets** (Prepregs): These are pre-impregnated sheets with reinforcements like carbon fibres in carbon-fibre-reinforced polymer (CFRP) composites [36], glass fibres (E-Glass) [37], or natural fibres like jute and sisal [38, 39]. It is used in aerospace for aircraft structures, wind turbine blades, and automotive lightweight construction, and they offer controlled resin content for consistent quality and are processed via autoclave or vacuum bagging for high strength to weight ratio [40].
b. **Layered epoxy-fibre structures** (Laminated): These are layered structures combining epoxy with fibres such as ultra-high modulus polyethylene (UHMPE), hybrid fibres (carbon and Kevlar), hemp/PET hybrids, or silica sand nanoparticle reinforcements for enhanced modulus, with studies showing improvements in stiffness and fracture energy (up to 20% increase with 5 vol% silica nanoparticles) and enhanced tensile and bending properties in glass fibre composites [41-44]. They are used in marine applications, industrial tooling (moulds and fixtures) and constructions for structural repairs, often prepared via hand lay-up or infusion process, providing corrosion resistance and durability [41].

Coatings

Epoxy resin coatings are applied for protective and decorative purposes across industrial, marine and domestic settings, leveraging their chemical resistance, minimal shrinkage, and durability. They are applied as:

a. **Liquid Coatings** (Paints and Primers): Often based on aliphatic epoxy resins for UV resistance, these are used as paints and primers for interior/exterior decoration in construction (like floors, basement wall), marine environments (ship hulls), and industrial flooring to protect against corrosion and water, with recent advancements focusing on structural modifications and functional fillers for enhanced anticorrosion performance under harsh conditions [45, 46].
b. **Powder Coatings**: Typically formulated with BPA based resins for improved adhesive properties, these are applied electrostatically and cured under heat, offering a durable finish for metal surfaces in appliances, automotive parts and outdoor furniture, providing excellent resistance to chemical and abrasion part of anticorrosion strategies [45, 47].

Encapsulants and Potting Compounds

Epoxy resin showcases excellent insulation and penetration properties, making it suitable for electronics and electrical applications. They are usually in liquid or paste form, poured into moulds or electronics, and often use cycloaliphatic epoxy resins for low viscosity or DGEBA for cost-effectiveness [48]. Application includes:

a. **Electronics Protection**: Used to encapsulate semiconductor devices and printed circuit boards (PCBs) in epoxy molding compounds (EMCs), safeguarding against moisture, dust, temperature variations and mechanical damage in devices like integrated circuits and transformers [48].

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b. **Electrical Insulation**: Applied in motors, generators, switchgear, and bushings to insulate windings and components, providing thermal stability (up to 150-200°C) and dielectric strength, with dielectric studies confirming performance variations with curing agent concentration and frequency [48].
c. **Industrial Sealing**: Used in sealing mechanical parts and assemblies in harsh environments, such as offshore structures, to prevent leakages and corrosion, often in paste form for gap-filling capabilities, aligning with epoxy's noted mechanical strength [48].

Additionally, epoxy resins are also used in other specialised forms like in casting resins (clear or pigmented form) [49], foams (lightweight core materials in aerospace and marine industries) [50], tooling boards (solid blocks used for machining moulds and prototyping) [51]. Each form of application leverages epoxy's inherent properties like adhesion, chemical resistance, and mechanical strength to meet diverse industrial, commercial, and consumer needs across an expanding range of sectors.

Fillers Used in Epoxy Resin System

Mineral Filler Systems

Mineral filler are most used fillers in commercial epoxy formulations due to their cost-effectiveness, well established processing methods and chemical stability [52]. Silica-based systems, including fumed silica and silica flour, serve multiple functionalities such as rheological control to mechanical reinforcement [53, 54]. The silica infusion also aids in interfacial adhesion, with silane-modified variants demonstrating superior mechanical properties and thermal stability compared to untreated alternatives [54, 55].

Calcium carbonate is another cost-effective mineral filler which provides bulk reinforcement and shrinkage reduction percent while maintaining good processability [55, 56]. Studies demonstrate that surface-modified calcium carbonate nanoparticles can achieve significant improvements in mechanical properties, with tensile strength increases of up to 33% reported in optimised formulations [57, 58]. Talc-based systems offer unique advantages in terms of workability and dimensional stability, particularly in applications requiring precise tolerances and smooth surface finishes [55, 59]. Another mineral based filler is wollastonite beads are small particles made of calcium silicate ($CaSiO_3$) used as reinforcing fillers in epoxy composites. Researchers found that low-aspect-ratio wollastonite improved flexural strength and impact resistance, while high-aspect-ratio types enhanced flexural modulus, confirming their effectiveness in strengthening epoxy systems [60, 61].

Ceramic Filler Systems

Ceramic filler enables thermal management capabilities that are essential for electronic packaging, aerospace applications, and thermal interface materials [62]. Ceramic like aluminium oxide and aluminium nitride fillers provide thermal conductivity enhancements while maintaining electrical insulation [63]. The particle size distribution and morphology of ceramic fillers critically influence both the maximum achievable loading and the resulting composite properties [63].

Boron nitride systems are also used to achieve superior thermal conductivity capabilities, with some formulations achieving up to five times improvement over unfilled epoxy matrices [64]. Silicon carbide and aluminium nitride represent the highest performance ceramic options,

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enhancing thermal conductivity values approaching those of metals while maintaining the processing advantages of polymer composites [63, 65]. However, these advanced ceramic systems require specialised surface treatments and processing protocols to achieve optimal dispersion and performance [65].

Carbon Based Nanofillers

These nanofillers provide combinations of electrical conductivity, mechanical reinforcements, and thermal management capabilities which are necessary for electromagnetic interference shielding and conductive adhesive applications [66, 67]. Multi-walled carbon nanotubes demonstrate exceptionally low electrical percolation thresholds, typically around 0.47 weight percent, with electrical resistivity values reaching 5.1×10^{-8} Ω.m in optimised systems [68]. The functionalization of carbon nanotubes through covalent attachment of carboxyl, ester, or epoxy groups significantly improves dispersion quality and interfacial adhesion [68].

Graphene and graphite-based filler systems are used as a cost-effective alternative for applications requiring moderate electrical conductivity and lubricity enhancement [69], with recent study showing that thermally expanded graphite can have low electrical resistivity of up to 7.5×10^{-6} Ω.m with percolation thresholds around 5 weight percent [68]. Carbon black remains the most cost-effective option for basic electrical conductivity requirements, which offers reliable performance for antistatic applications and EMI shielding [70].

Metallic Filler Systems

These systems are used in critical electronic interconnections and thermal management systems due to their superior electrical and thermal conductivity [71, 72]. Epoxy composites filled with copper and nickel shows percolation-type electrical conductivity, with thermal conductivity of 35 W/mK and 13 W/mK respectively [73].

Aluminium and nickel-based systems are more cost-effective alternatives for applications where moderate electrical and thermal conductivity are sufficient [74]. Likewise, copper and brass fillers are also used as another economical alternative, but similar to other metallic filler, the high loading requirements and associated processing challenges often limit the widespread use in high-performance applications [75].

Bio-based and Sustainable Alternatives

Bio-based materials like wood flour and natural plant fibres have been used in 5-30 weight percent loading, contributing to improved mechanical properties and sustainability profiles of the epoxy systems [76]. Likewise, materials like coffee derived biochar as a sustainable flame-retardant filler, has shown enhanced fire resistance properties and environmental benefits [77].

The major filler categories used in epoxy resin matrices are summarised in Table 2.

Table 2. Types of fillers used in the epoxy resin matrix

Filler Type	Example Materials	Applications/Key Effects
Mineral	Silica flour, CaCO3, talc	Thickening, bulk strength, cost reduction
Ceramic	Al2O3, AlN, SiC, BN, quartz	Thermal conductivity, abrasion resistance

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Glass-based	Glass spheres, milled glass	Lightweight, easy sanding, structural strength
Carbon-based	Carbon black, graphite, fibres	Strength, conductivity, lubricity
Metallic	Al, Ag, Ni W	Electrical/thermal conductivity
Natural/Bio-based	Wood flour, plant powders	Sustainability, colour, texture
Functional Additives	Pigments, Fire retardants	Colour, fire resistance, UV Stability

Challenges in Recycling Epoxy Resins

Thermoset vs Thermoplastic Recycling Challenges

Epoxy resins belong to the thermoset polymer class, which undergo irreversible crosslinking during curing, forming a rigid three-dimensional network [78]. Unlike thermoplastics, which soften upon heating and can be reprocessed, thermosets cannot be remelted or reshaped due to their covalent crosslinks [78]. This fundamental distinction renders conventional mechanical recycling, grinding and remoulding, ineffective for epoxies, as the process degrades mechanical properties and produces low value filler materials [79]. For example, recycled epoxy particles from wind turbines or aerospace composites exhibit reduced tensile strength and are limited to non-structural applications like roadbed additives [78]. In contrast, thermoplastic dominates recycling streams due to their compatibility with melt-reprocessing, accounting for 18% of global plastic recycling rates, while thermosets like epoxy remain underrepresented [79, 80].

The crosslinked structure of epoxies also complicates chemical recycling. While thermal methods such as pyrolysis (400-800°C) can decompose epoxy matrices into syngas or char, the process demands high energy inputs and releases toxic byproducts like dioxins and hydrogen chloride [79]. Emerging solvent-based approaches using ionic liquids (like alkyl-methyl-imidazolium salts) or transesterification catalysts show promise for cleaving crosslinks under milder conditions (~150°C) [81, 82]. However, these methods struggle with scalability due to the need for pure feedstock and costly catalysis, unlike thermoplastic recycling, which tolerates mixed waste streams [78]. Additionally, the strong adhesion of epoxies to other materials, such as in composites, makes separation for recycling technically unfeasible in many cases, further limiting recovery options [78].

Durability, Chemical Resistance and Economic Constraints

The high durability and chemical resistance of epoxy resins are critical for applications like marine coatings and aerospace composites, which creates a paradox in recycling. Their resistance to acids, solvents and UV degradation necessitates aggressive treatments for depolymerisation, which often degrade recovered components. For instance, nitric acid digestion of carbon-fibre reinforced epoxy composites (CFRECs) recovers fibres but corrodes their surfaces, reducing tensile strength by 20-40%. Similarly enzymatic or microbial degradation, effective for polyesters like PET, fails to break epoxy's aromatic backbone due to their lack of evolved biochemical pathways.

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Economically, epoxy recycling faces viability challenges. Mechanical recycling yields materials valued at <€500/tonne, compared to virgin epoxy resins priced at €3,000-5000/ tonne [78, 83]. Chemical recycling methods, though capable of recovering high-purity monomers, incur cost from catalysts and energy-intensive steps, making them 30-50% more expensive than landfilling [81, 84]. Furthermore, epoxy resins often constitute <10% of composite materials like in wind turbine blades, rendering separation and recovery economically unjustified [83]. The European Composites Industry Association estimates that recycling CFRECs costs €1500-2000/tonne, while landfilling costs €100-200/tonne [83].

Waste Management Challenges and Environmental Impact

Global epoxy-specific waste generation and recycling rates are not reported consistently enough to support a robust worldwide estimate. The frequently cited projection of approximately 12,000 Mt by 2050 applies to cumulative plastic waste in landfills or the natural environment, rather than to epoxy waste alone [6]. Epoxy waste nevertheless presents a persistent management challenge because cured networks are not readily biodegradable and may contain additives such as phthalates and brominated flame retardants [80]. Landfilling loses material value, while incineration can generate greenhouse gas and toxic emissions, including polychlorinated dibenzofurans, unless appropriate controls are used [78, 80]. The burden can be particularly significant for epoxy-containing electrical and electronic products, in which hazardous constituents complicate treatment and disposal [29].

Composite waste compounds these challenges. Wind turbine blades, containing epoxy-glass fibre composites, accumulate at a rate of 400,000 tonnes annually, with limited infrastructure for fibre-matrix separation [79, 83]. Pyrolysis of these composites recovers fibres but leaves a resin char residue requiring hazardous waste handling [79, 85]. Emerging bio-based epoxies, while recyclable via mild acid hydrolysis, face scalability barriers due to 2-3 times higher production costs than conventional resins [84, 85]. The increasing demand for epoxy-based composites in sustainable technologies like wind power and electric vehicles amplifies the urgency for effective recycling solutions to manage this waste stream [79].

Recycling Technologies for Epoxy Resins

The very properties that make epoxy resins desirable also render them difficult to recycle posing significant challenges to achieving a circular economy. This section critically reviews the state-of-the-art recycling technologies for epoxy resins, emphasising their potential to align with circular economy principles. The discussion spans chemical, thermal, mechanical and composite specific recycling approaches, as well as emerging hybrid methods that promote to bridge current technology gaps. Commercial and emerging epoxy recycling technologies are compared in Table 3. Throughout this section, ‘neat epoxy’ refers to cured resin without fibre reinforcement, whereas ‘epoxy composite’ refers to an epoxy matrix containing reinforcement. Outcomes are identified as resin or chemical recovery, fibre recovery, or combined recovery, as applicable.

Mechanical Recycling

Mechanical recycling is a straightforward approach that physically processes epoxy waste into smaller particles or fibres for reuse in composite materials, offering a low-cost option for downcycling despite not recovering monomers or oligomers. Technologies such as high-energy ball milling and ultrasonication are commonly employed to pulverise cured epoxy composites into fine powders or short fibres [86]. These recycled fillers can be reintegrated into new composite formulations at concentrations ranging from 15% to 27%, achieving mechanical properties comparable to virgin materials in non-structural applications [8]. However, mechanical recycling often leads to reduced

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material properties due to filler size reduction and contamination. This limitation restricts its use to low-value products, underscoring the need for advanced methods to recover high-performance materials from epoxy waste.

Thermal Recycling

Thermal recycling methods involve the application of heat to decompose epoxy resins either for energy recovery or material reclamation. While these methods are widely used due to their simplicity, they often result in the loss of valuable matrix materials and pose environmental concerns.

Pyrolysis

Pyrolysis is a high-temperature process (typically around 550°C) that decomposes the resin matrix of fibre-reinforced epoxy composites into gaseous, liquid, and solid products while enabling recovery of the reinforcing fibres [85]. For carbon-fibre-reinforced polymer (CFRP) composites, reported fibre recovery can exceed 90% [85]. The primary outcome is therefore fibre recovery; the epoxy matrix is converted into pyrolysis products rather than recovered as intact resin. Pyrolysis is energy intensive and can impair fibre properties if oxidation is not adequately controlled [87]. Gaseous and liquid products may also require further treatment before use or disposal.

Incineration with Energy Recovery

Incineration with energy recovery involves combusting neat epoxy waste or the resin fraction of epoxy composites at high temperature. It reduces waste volume and may recover energy, but it destroys the resin and does not provide resin recovery. For glass-fibre reinforced composites (GFRCs), the residual glass fibre generally has reduced value and may require additional processing [88]. Greenhouse-gas and other emissions must be controlled through appropriate flue-gas treatment [89].

Table 3. Commercial and Emerging Epoxy Recycling Technologies

SN	Technology/Developer	Process	Recovered materials	Commercial status	Ref
1	Cleavable Bond Recycling Connora Technologies	Acid degradation with base precipitation	Thermoplastic polymers with intact fibres	Commercialised	[90]
2	Solid Catalyst Decomposition University of Tokyo	Proprietary solid catalyst system	Original materials for reuse	Commercialised	[91]
3	Amino Compound Plasticization Hitachi Chemical	Amino compounds for plasticizing with rehardening	New thermoset products	Patented	[92]
4	Ionic Liquid Dissolution	Alkyl-methyl-imidazolium ILs with alcohol	Epoxy monomers intact carbon fibres	Advanced Research	[81]
5	Vitrimer Technology Sichuan University	Glutathione assisted	Carbon fibres, adhesive precursors	Research with commercial applications	[93]

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		thioldisulfide exchange			
6	Conventional Pyrolysis ELG Carbon Fibre	Controlled atmosphere thermal decomposition	Clean carbon fibres	Commercialised	[94]
7	Microwave Pyrolysis	Microwave assisted thermal decomposition	Carbon fibres with minimal sizing loss	Commercialised	[95]
8	Mechanical Recycling	HADEG Recycling, Boeing, Airbus	Fibre rich particles for reinforcement	Widely implemented	[96]
9	Hybrid Mechanical Thermal CFK Valley Stade Recycling	Sequential mechanical and thermal processing	Higher quality recyclable	Commercialised	[97]
10	Solvolysis Adherent technologies	Subcritical solvent treatment	Clean fibres and decomposed resin	Commercialised	[98]

Chemical Recycling of Epoxy Resins

Chemical recycling is a promising approach that involves breaking down the crosslinked network of epoxy resins into reusable monomers or oligomers. This method offers the potential for high value recovery of both the resin matrix and reinforcing fibres.

Solvolysis and Depolymerisation

Solvolysis is one of the most extensively studied chemical recycling methods for epoxy resins. It involves the use of solvents and catalysis in depolymerise the resin matrix. For instance, ethylene glycol (EG) combined with catalysts such as 1,5,7-triabicyclo [4.4.0] dec-5-ene (TBD) has been shown to efficiently degrade epoxy-anhydride systems at temperature ranging from 150°C to 180°C [85, 87, 99]. This process not only dissolves the resin but also preserves carbon fibres (CFs) with minimal damage, retaining over 90% of their original tensile strength [99].

Recent advancements have introduced ionic liquids (ILs) as green solvents for solvolysis. For example, 1-butyl-3-methylimidazolium chloride ([BMIm][Cl]) has demonstrated complete dissolution of thermoset epoxy resins at 150°C under atmospheric pressure [81]. The recovered monomers can be re-polymerised into new resin systems with properties comparable to virgin materials. Despite these successes, challenges such as solvent recovery and scalability remain significant barriers to industrial adoption.

Enzymatic Degradation

Enzymatic recycling represents an eco-friendly alternative that operates under mild conditions (30-40°C). Enzymes such as lipases have been employed to hydrolyse ester linkages in epoxy-polyurethane composites [100]. While this method minimises environmental impact and energy consumption, its reaction rates are slow, and scalability is limited by enzyme availability and cost. Recent research

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focuses on metagenomic approaches to discover novel enzymes capable of degrading highly crosslinked epoxy networks [100].

Emerging Hybrid Methods and Future Trends

Hybrid recycling methods combine chemical, thermal or mechanical processes to optimise material recovery while minimising environmental impacts. These approaches represent the frontier of epoxy resin recycling research.

Catalytic Hydrogenation

It employs bimetallic catalysts such as Ni-Pd/CeO_2 to depolymerise epoxy networks at moderate temperatures (≈180°C) [91]. This method efficiently recovers phenolic compounds and undamaged fibres while reducing energy consumption by up to 60% compared to pyrolysis [91]. However, its reliance on precious metals poses cost challenges that must be addressed through catalyst optimisation or substitution.

Ionic Liquids and Supercritical Fluids

Ionic liquids (ILs) combined with supercritical fluids offer a versatile platform for dissolving thermoset networks under mild conditions (≈150°C) [81, 101]. For instance, mixture of [BMIm][Cl] and ethylene glycol have achieved complete dissolution of thermoset epoxy resins within 2-3 hours under atmospheric pressure [81]. These methods are particularly promising for high-value applications but require further development for large-scale implementation.

Advances in Bio-based and Recyclable Epoxy Resins

The field of bio-based and recyclable epoxy resins has witnessed remarkable progress in recent years, driven by the urgent need for sustainable alternatives to petroleum derived thermosets. These advances have focused on addressing two critical challenges: replacing fossil-fuel based raw materials with renewable resources and developing reprocessable or degradable networks to overcome the inherent recyclability limitations of traditional crosslinked epoxy systems. Significant breakthroughs have been achieved in deriving epoxy precursors from plant oils, lignin, vanillin and other renewable resources, while dynamic covalent chemistry has enabled the creation of recyclable epoxy networks with comparable performance to conventional systems. This section examines the current state of development, recent innovations and practical applications of these sustainable materials. In this review, these attributes are distinguished explicitly: ‘bio-based’ denotes partial or complete derivation from renewable biological feedstocks; ‘biodegradable’ denotes breakdown by biological activity under specified conditions; ‘recyclable’ denotes the capacity for material recovery through a defined recycling route; and ‘reprocessable’ denotes the capacity of a cured network to be reshaped or remoulded, typically through dynamic or reversible bonds. A bio-based epoxy is therefore not inherently biodegradable, recyclable, or reprocessable unless those properties are separately demonstrated.

Renewable Feedstocks and Their Modifications

Plant derived compounds have emerged as promising alternatives to synthesize epoxy resins with sources like lignin, vanillin and plant oil as commonly used sources.

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a. **Lignin-Derived Epoxy Systems**: Lignin, a major byproduct of the pulp and paper industry, is an abundant aromatic polymer that can be directly epoxidized or depolymerised to yield phenolic monomers such as vanillin [102]. Lignin-based epoxies have been cured with both aromatic and aliphatic amines, demonstrating high thermal stability and mechanical strength [103]. The use of lignin not only valorises a waste stream but also imparts flame retardancy and environmental resistance to the resulting networks.
Vanillin, is a lignin derivative, enables high-performance flame-retardant systems, which shows excellent mechanical strength too making them suitable in applications like coatings, adhesives and electronics [102]. Wang et al, developed a vanillin-derived diglycidyl ethers with phosphorous containing groups, achieving UL-94 V-O ratings (self-extinguishing within 3 seconds) while maintaining glass transition temperature (T_g) of 160-180 °C [104]. These resins show 30% reduced peak heat release rates compared to DGEBA, making them viable for aerospace composites.

b. **Plant-Oil Based Epoxy Resins**: Plant oils are among the most widely studied bio-based sources for epoxy resin synthesis. Their triglyceride structure, rich in unsaturated fatty acids, provides multiple reactive sites for epoxidation [105]. Oils such as soybean, linseed, canola, castor, and Karanja have been successfully converted to epoxidized derivatives using chemical or enzymatic methods. Epoxidized soybean oil (ESO) is commercially available and has been used to develop resins with promising mechanical and shape-memory properties, although its long aliphatic chains can limit rigidity and thermal resistance [105]. Modification strategies, including acrylation or hybridization with inorganic fillers, have been shown to enhance mechanical properties and broaden application potential. Linseed and castor oils, with high degrees of unsaturation, yield epoxies with improved crosslink density and thermal properties, making them suitable for composite matrices and coatings [106]. Karanja oil, a non-edible resource, has also been epoxidized and demonstrated high thermal stability and potential for speciality applications such as coatings and mosquito deterrents [107].

c. **Saccharide-Derived Epoxy Resins**: This kind of epoxy utilizes carbohydrates such as isosorbide and furan derivatives, offering rigid cyclic structures that impart stiffness and high glass transition temperatures (T_g) to the resulting polymers [108]. Isosorbide-derived epoxies, for instance, have been synthesized via reaction with epichlorohydrin and can be cured with isosorbide diamine hardeners to yield fully bio-based networks [108]. These resins demonstrate good mechanical strength and are promising for applications requiring food safety and biodegradability, though their hydrolytic stability in wet environments remains a challenge [108]. Furan-based epoxies, derived from 2,5-bis(hydromethyl)furan (BHMF) and 2,5-furandicarboxylic acid (FDCA) have shown high T_g and mechanical strength with potential for use in adhesives, coatings, and high-performance composites [109]. The aromaticity and rigidity of the furan ring structure contribute to their desirable properties, and recent studies have demonstrated their suitability as replacements for petroleum based phenolic epoxies [110].

d. **Polyphenol and Phenol-Based Epoxy resins**: Polyphenols such as tannins and cardanol (from cashew nutshell liquid) provide aromatic structures that enhance the chemical resistance and thermal stability of epoxy networks [111, 112]. Tannin derived epoxies, particularly those based on catechin, have been synthesized and cured with natural lignin-based hardeners, yielding high T_g values and mechanical strength

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comparable to bisphenol-A (BPA) based resins [111]. Cardanol-based epoxies, while flexible due to their long aliphatic side chains, can be blended with saccharide-derived epoxies to improve rigidity and thermal properties [112]. The combination of different bio-based monomers allows for the fine tuning of network properties, making these resins suitable for coatings, adhesives and electronic encapsulations.

e. **Natural Resin-Derived Epoxy resins**: Terpenes, rosin and natural rubber are additional sources of bio epoxy resins. Resin derived from pine and conifer trees, is rich in rigid, fused-ring structures that impart high T_g and modulus to the resulting epoxies [113]. Recent work has demonstrated that resin-based epoxies, such as tetraglycidyl dimaleopimaryl ketone (TGK), can achieve thermal and mechanical properties on par with or superior to conventional BPA based resins, making them attractive for coatings and high-performance composites [114]. Epoxidized natural rubber (ENR) is used primarily as a toughening agent in epoxy matrices, enhancing impact strength and flexibility in fibre-reinforced composites for automotives and industrial applications [115]. The main types of bio-based epoxy resins are presented in Table 4.

Table 4. Different Types of Bio-epoxy Resin [102, 107, 108, 110]

Resin Type	Source/Monomer	T_g (°C)	Key Properties	Applications
Epoxidized Soybean Oil (ESO)	Soybean Oil	-60 to 33	Flexible, shape-memory, low rigidity	Coatings, shape-memory polymers
Epoxidized Linseed Oil (ELO)	Linseed Oil	68-134	High crosslink density, improved mechanicals	Composites, adhesives, laminates
Isosorbide based Epoxy	Isosorbide	43-125	Rigid, high strength, biodegradable	Food-safe coatings, encapsulants
Furan based epoxy	2,5-FDCA, BHMF	71-152	High Tg, strong, aromatic	Adhesives, composites, coating
Tannin-based epoxy	Catechin, green tea	142-179	High modulus, chemical resistance	Coatings, electronics
Cardanol-based epoxy	Cashew nutshell liquid	15-83	Flexible, hydrophobic	Coatings, adhesive
Rosin-based epoxy	Pine/conifer rosin	15-93	Flexible, hydrophobic	Coatings, adhesive
Lignin-based epoxy	Kraft/organosolv lignin, vanillin	74-98	High thermal stability, flame retardant	Adhesives, electronics
ENR toughened epoxy	Natural rubber	-	High impact strength	Automotive composites

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Bio-based Epoxies with Dynamic Covalent Bonds

Reversible chemistries such as dynamic covalent bonds are being integrated into bio-based epoxies to enable reshaping and reprocessing at end-of-life stages [12]. For example, phosphonate-based epoxies developed by Empa researchers exhibit both flame retardancy and recyclability through bond reorganization at elevated temperatures (≈200°C) [116]. These innovations align closely with circular economy principles by facilitating closed-loop material cycles without compromising performance. Recent research, such as the glutathione-assisted thiol-disulfide exchange in vitrimer technology, demonstrated the ability to recover carbon fibres and adhesive precursors with up to 90% retention of mechanical properties after multiple recycling cycles, offering a sustainable pathway for high value applications [117]. Examples of commercially available bio-based epoxy resins are provided in Table 5.

Table 5. Commercially available Bio-based Epoxy resins

Name	Content	Features	Applications	Ref
SuperSap (Entropy Resin)	Bio-based carbon content derived from feedstocks like plant oil	Compatible with traditional curing agents	Surfboards, furniture, and composites	[118]
Greenpoxy (Sicomin)	28-55% bio-based content from plant-based materials	High mechanical properties and customizable formulations	Marine applications, sports equipment	[119]
ECO-UVR (Cardolite)	Cashew nutshell liquid based phenolic compounds	Excellent UV resistance and high bio-content	Coatings, adhesives and electronics	[120]
Recyclamine (Connora Technologies)	Cleavable acetal-based curing agents for bio-based epoxy systems	Fully recyclable thermoset,	Electronic and automotive parts	[90]
Epicerol (Solvay)	Glycerol derived epichlorohydrin (100% biobased)	Drop-in replacement for conventional epichlorohydrin	Coatings, adhesives and composites	[121]
Ellum Resin (Arkema)	Thermoplastic resin with partial bio-content from renewable sources	Recyclable with depolymerisation and suitable for liquid moulding processes	Wind turbine blades and automotive parts	[122]

Figure 2 provides a comprehensive overview of the current landscape of bio-based and recyclable epoxy systems. Renewable feedstocks such as lignin, vanillin, plant oils, cardanol, rosin, and isosorbide are increasingly being utilised to replace petroleum-derived precursors, reducing dependence on fossil resources. These bio-based materials are being combined with advanced recyclable epoxy designs, including dynamic covalent bonding, vitrimer networks, cleavable linkages, and reversible curing chemistries, which enable network rearrangement, repairability, and reprocessability. The integration of these approaches has led to significant benefits, including lower carbon footprints, enhanced

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resource efficiency, fibre recovery, shape memory behaviour, and improved end-of-life management. Despite these advances, challenges remain in terms of production costs, industrial scalability, long-term durability, catalyst requirements, and regulatory acceptance. Figure 2 also highlights key application areas, including wind energy, automotive, aerospace, electronics, coatings, construction, and marine sectors, while outlining future research directions focused on high bio-content formulations, scalable vitrimer technologies, closed-loop composite recycling, AI-assisted material design, and life-cycle sustainability optimisation. Collectively, these developments demonstrate the potential of bio-based recyclable epoxy systems to support a circular and sustainable materials economy.

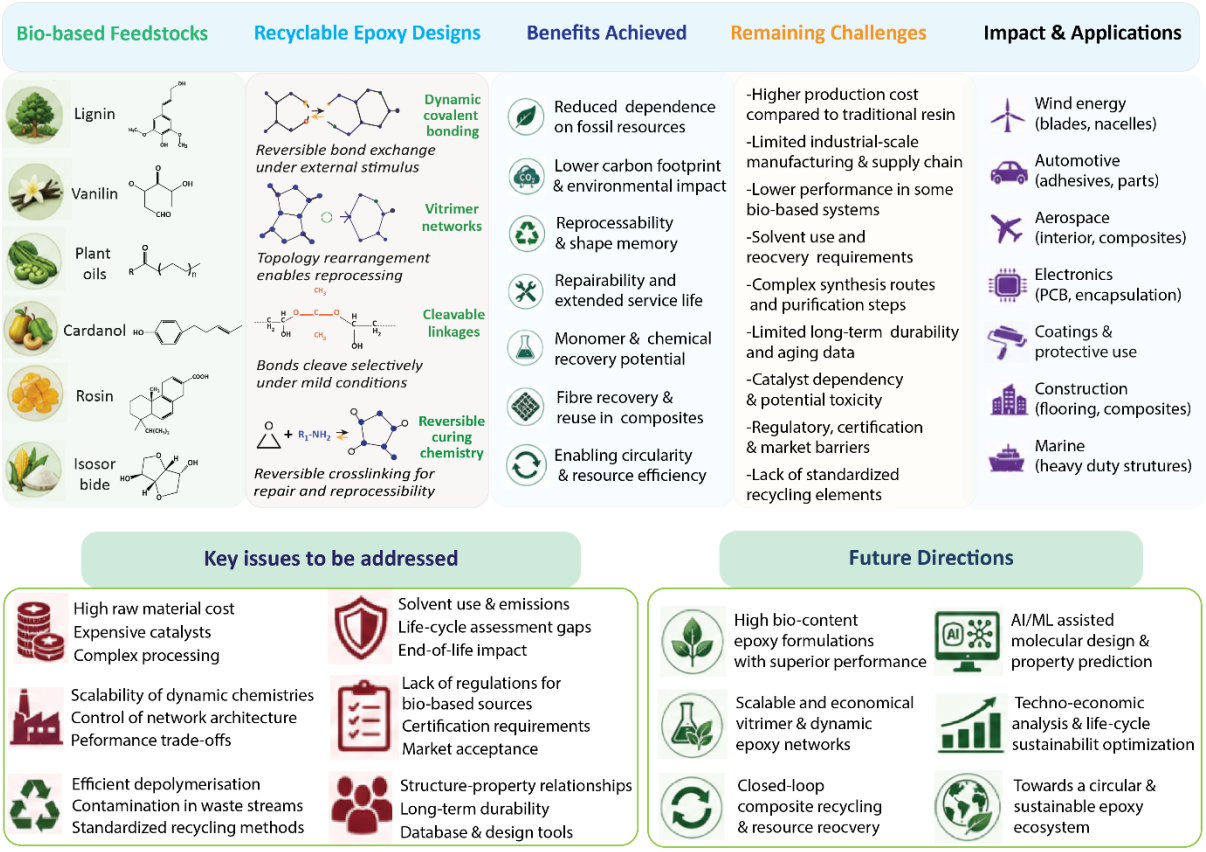


Figure 2. Overview of bio-based and recyclable epoxy resin systems: renewable feedstocks, recyclable network designs, benefits, challenges, industrial applications, and future research directions. The figure highlights the integration of bio-derived precursors with dynamic covalent chemistries to enable sustainable, circular epoxy materials.

Patent Landscape Analysis in Epoxy Recycling

The patent landscape for epoxy recycling reflects a growing interest in addressing the environmental and economic challenges posed by epoxy waste. A surge in patent filings over the past decade, aligns with global push toward circular economy principles and stricter waste management regulations. The innovation trend reveals a shift from traditional disposal methods to advanced recycling techniques capable of reclaiming both the polymer matrix and reinforcements. Early patents focused primarily on mechanical grinding and incineration, but recent filings emphasize sustainable approaches, including chemical decomposition and low-energy thermal processes [123]. These processes necessitate specific patent classifications to capture innovations effectively, particularly on an international level where the International Patent Classification (IPC) and Cooperative Patent Classification (CPC) systems are used.

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Patent Classifications Relevant to Epoxy Recycling

The primary patent classification for epoxy recycling is IPC C08J11/00, which in the IPC covers, “Recovery or working-up of waste materials of plastics” [124]. This classification is highly relevant as epoxy is a thermoset plastic, and patents related to its recycling, such as mechanical grinding or chemical breakdown, are often classified here. However, there is some complexity in classification between IPC and CPC. In CPC, C08J11/02 is defined as “Recovery or working up of waste materials of inorganic materials”, which may seem inconsistent for plastic recycling. In practice, many patents still use C08J11/02 for plastics, likely due to the retention of IPC classifications [124]. This overlap highlights the need for clearer categorization to streamline innovation tracking in epoxy resin recycling.

For epoxy specific aspects, IPC C08G59/00 is another critical classification, covering “Polycondensates containing more than one epoxy group per molecule” [125]. This is relevant for patents that involve the chemistry of epoxy resins, such as those detailing new curing or degradation methods. For instance, EP1085044B1, titled, “Method for recycling thermoset epoxy resin materials”, is classified under both IPC C08G59/00 and IPC C08J11/00, indicating a dual focus on epoxy chemistry and waste recovery [126].

Environmental classifications also play a role, particularly under the CPC’s Y02W series. CPC Y02W30/50 (“technologies for solid waste management, specifically reuse, recycling, or recovery technologies”) and Y02W30/62 (“Plastics recycling;Rubber recycling”) are often tagged for patents with sustainability benefits [127], as seen in EP1085044B1 [126]. This reflects the growing emphasis on green technologies, aligning with circular economy trends as highlighted in recent studies. The relevant IPC/CPC classifications are summarised in Table 6.

Table 6. Common CPC/IPCR Classification for Epoxy Resins and its Recycling [124, 125, 127]

IPC/CPC Classification	Description
C08G59/00	Macromolecules obtained by reaction of epoxy polycondensates with monofunctional low-molecular-weight compounds;
C08G59/02	Polycondensates containing more than one epoxy group per molecule
C08G59/50	Polycondensates containing more than one epoxy group per molecule with amine hardeners
C08K3/00	Use of inorganic substances as compounding ingredients as additives in polymer
C08J11/00	Recovery or working up of waste materials (polymeric)
C08J11/06	Recovery or working up of waste materials (polymeric) without chemical reactions
C08J11/24	Recovery of polymeric waste with inorganic material (containing hydroxyl groups)
C08J11/28	By treatment with organic compounds containing N, S or P
C08L63/00	Composition of epoxy resins and its derivatives

Overview of Patent Activity for Epoxy Resin and Its Recycling

A comprehensive analysis of the patent database using “lens.org” was conducted, focusing on section 5.1 classification and groups for epoxy resin and its recycling (Figure 3). This

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analysis organises patent records chronologically, examines emerging trends, and classifies them according to relevant patent categories, including subgroup classifications (Figure 4). Additionally, it provides a regional overview of developments in epoxy resin recycling offering insights into the geographical distribution of research and innovation in this field (Figure 5).

A growing trend in patent filing and grants for epoxy resins and its recycling can be observed with notable growth from 2015, in a global scale. US and Europe seem to be a clear front runner in this scope with Australia been trailing far behind, as seen from data from 1980 till present [128].

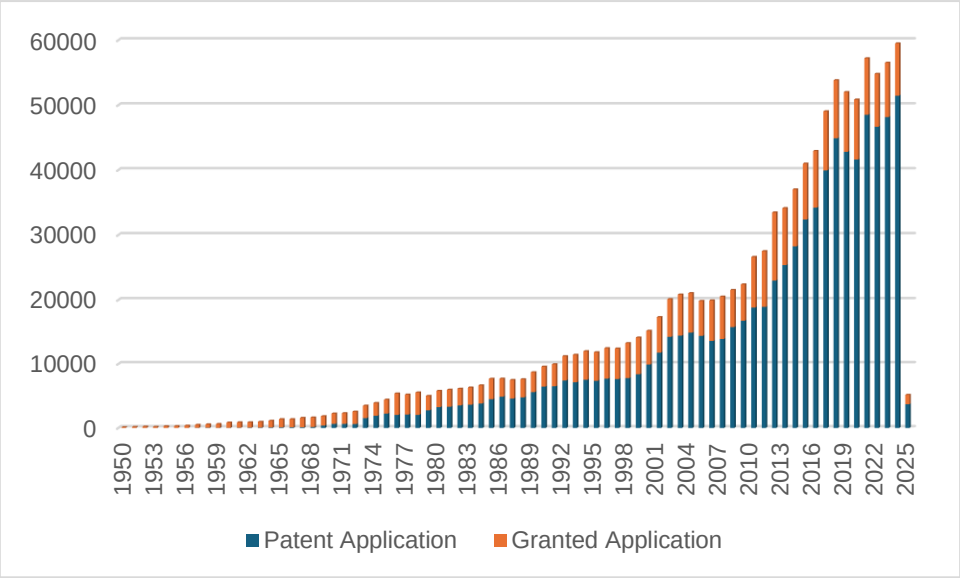


Figure 3. Patent application and grants for epoxy resin recycling by date [128]

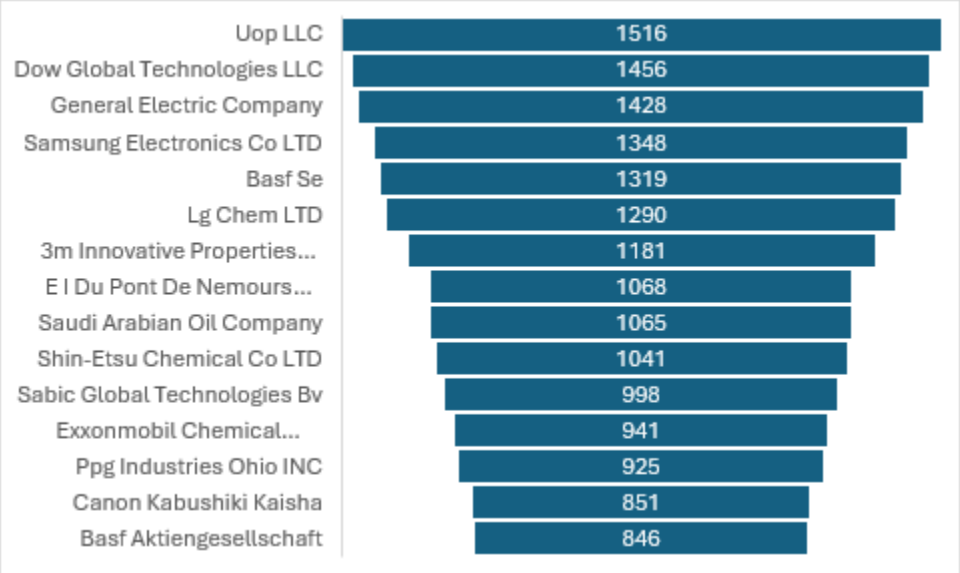


Figure 4. Patent Owner Jurisdiction Distribution [128]

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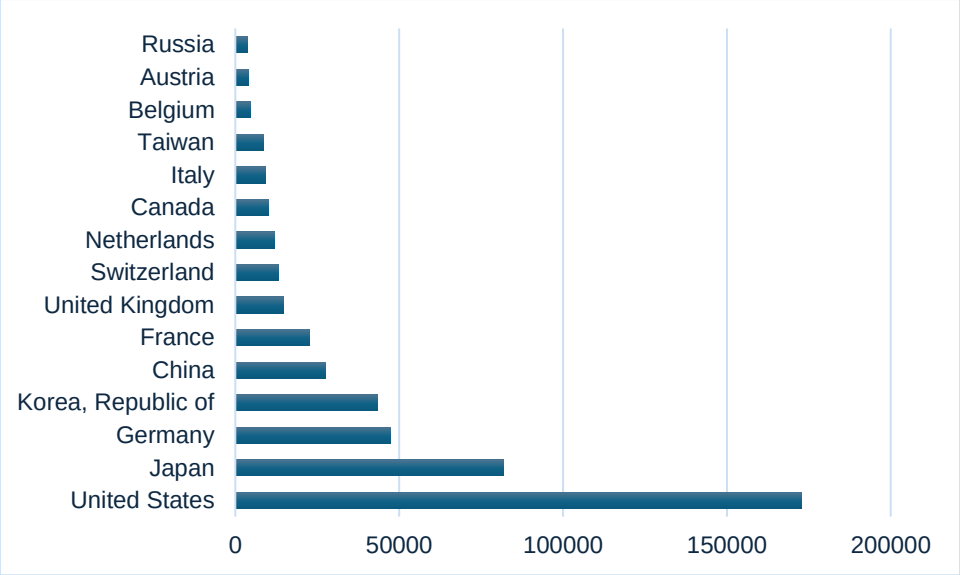


Figure 5. Patent Application by Country for Epoxy resin and its recycling [128]

Similarly, the evolution of epoxy recycling has followed a clear trend, shifting from simple mechanical separation to advanced chemical process capable of breaking down even the most resistant materials. Based on the number of document count in IPC and CPC classification for epoxy resin and its recycling, the early stage of resource recovery relied heavily on mechanical separation and reprocessing (B29B17/02, B29B2017/0293). As demand for efficient recycling grew, thermal methods (C08J11/12) gained traction, though it still shows an inherent trend of downcycling epoxy resin which produced low-value char and gases from epoxy resin. Thus, the research has been focused on chemical recycling which allows resin to be broken down into their fundamental building blocks. This pattern can be clearly observed from increase in the document count for classification like C08J11/08/10/28/16 and B29B2017/0293/04, which focuses on solvent-based recovery, chemolysis, hydrolysis, specialised organic reactants and treatments. This shift towards chemical methods reflects a broader commitment to high-value material recovery, aligning with circular economy goals.

Apart from most of the overlapping patent classification from IPCR/CPC, there are few groups that stand out and has prominent presence in the patent analysis for epoxy resin recycling. CPC classification has introduced separate Y02-classification to tag already existing documents which incorporates technologies or general process for mitigation or adaptation against climate challenges [129, 130]. This helps in systematic identification and keeping track of new technologies and work on sustainable technologies. For epoxy recycling following Y02 subgroups has been identified: Y02P10/20 (Climate change mitigation technologies in the production or processing of goods in recycling), Y02W30/62 (Reuse, recycling or recovery technologies for plastic and rubber), Y02W30/91 (use of waste materials as filler for mortars or concrete) and Y02E60/10 (Enabling technologies with a potential to mitigate GHG emission with application in energy storage batteries) [128]. Representative patents concerning epoxy resin recycling are listed in Table 7.

Table 7. List of Patents in Epoxy resin Recycling and Recyclability

Identifier/Grant Date	Title	Description	Ref

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US12215185 B2 (04 Feb 2025)	Recyclable and reworkable epoxy resins	A two-step process for thermoset epoxy recycling by plasticizing using an amino compound and re-hardening it with two-epoxy group (at least) compounds	[131]
EP4238954 A1	Bisphenol production method, recycled polycarbonate resin production method	A chemical recycling method for degrading polycarbonate resin into bisphenol using aromatic monoalcohol, water and catalysts like NaOH	[132]
US 4132718A (2 Jan 1979)	Preparation of liquid epoxy resins from bisphenol	A method for producing recyclable epoxy resins through azeotropic distillation of epichlorohydrin (ECH) and precise control of reaction parameters.	[133]
US2023/0295414 A1	A slow reacting recyclable epoxy resin system for structural composites	It uses a curing agent that includes cleavage linkage (of acetal, ketal or siloxy), which can be broken down in an acid solution for allowing recovery of reinforcement materials like fibres and converting epoxy resin into a thermoplastic polymer.	[134]
US2024/0182630 A1	Recyclable and decomposable epoxy resins: Compositions, preparation methods and applications in carbon fibre reinforced composites	Epoxy resin with thermal aldehyde groups allowing for decomposition and chemical recycling (organic solvents or amines) with >90% property retention	[135]
CN 116444765 A	Recyclable bio-based epoxy resin as well as preparation method and application thereof	Cardanol based epoxy resin with ester exchange catalyst for recyclability enabling recycling of carbon fibre composites made with this resin	[136]
US 2023/0183440 A1	Chemoenzymatic degradation of epoxy resins	Degradation of epoxy composites using multistep mild bio-based enzymes (glutathione S=transferase) and chemical (NaOH) degradation process with >90% resin removal	[137]
WO 2024/121807 A1	Recyclable sandwich structure composites	Core sheet (made of recyclable resin) sandwiched in two skins sheets made of reinforcing fibres and recyclable epoxy resin, where epoxy resin is made of dynamic curing agent with cleavable bond (ester/amide) allowing effective degradation of resin	[138]

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CN104194038A (2014)	Ultrasonic epoxy degradation	Enables recycling via solvent-assisted ultrasonic breakdown for epoxy resin with hydrolysable ester bonds through pulverizing, and non-proton polar solvent for swelling	[139]
CN111471214B	Methods of recycling epoxy molding compound	Extracting silicon dioxide filler using thermal cracking method (which can be used to reinforce polymers) from electronic packaging waste	[140]

Sustainability Aspects of Epoxy Resin Recycling

Life Cycle Assessment (LCA) of Epoxy Resins

Life Cycle Assessment has emerged as a critical methodology for evaluating the environmental impact of epoxy resin systems across their entire life cycle. LCA considers multiple stages: raw material extraction, manufacturing, use, and end-of-life (EoL) management. This comprehensive approach is particularly valuable for thermoset epoxy resins, which traditionally present significant end-of-life challenges due to their crosslinked nature.

Environmental Impact Metrics

The environmental burden of virgin epoxy production is substantial, with carbon emissions averaging approximately 5 kg CO_2 equivalent per kilogram of petroleum-based resin [141]. According to detailed LCA studies, epoxy resin synthesis contributes significantly to environmental impact, representing an 84.5% share of the total carbon footprint in automotive applications [141]. When examining glass fibre/epoxy composites specifically, the epoxy resin accounts for 68.9% of the environmental impact, while glass fibres contribute only 27.9% [142].

Energy consumption varies significantly across the life cycle stages. The extraction and processing of raw materials for epoxy resins represent the highest energy demand in the cradle-to-factory analysis [143]. According to comparative data, petroleum-based epoxy resins generate approximately 6663 kg CO_2 equivalent per tonne, while bio-based alternatives like SuperSap generate approximately 4079 kg CO_2 equivalent, a reduction of nearly 39% [143]. This significant difference extends to other environmental impact categories. The environmental impacts of petroleum-based and bio-based epoxy resins are compared in Table 8.

Table 8. Comparison of different types of Epoxy Resin [143]

Impact Category (Units)	Petroleum-based Epoxy	SuperSap Bio-based	Reduction (%)
Abiotic Depletion (kg Sb eq)	59.4	0.01	99.9%
Acidification Potential (kg SO_2 eq)	40.3	25.44	36.9%

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Global Warming Potential (kg CO_2 eq)	6663	4079	38.8%
Ozone-layer Potential (kg CFC11 eq)	1.26×10^{-6}	Not specified	-

These improvements are particularly significant when considering that epoxy resins typically constitute the largest contributor to environmental impact in composite structures. Bio-based epoxy alternatives derived from waste streams or co-products of other industrial processes demonstrate substantial environmental benefits without competing with food sources.

End-of-life Scenarios and Recycling Impacts

Different EoL scenarios significantly influence the overall environmental footprint of epoxy resin systems. Chemical recycling technologies have demonstrated potential to reduce carbon emissions by approximately 50% compared to virgin resin production [141]. When comparing energy requirements:

- **Mechanical recycling**: This approach exhibits the lowest energy demand at 0.27-2.03 MJ/kg but typically results in significant fibre degradation and downcycled products with reduced mechanical properties [141, 144].
- **Thermal recycling (Pyrolysis)**: Pyrolysis of epoxy composites particularly in wind turbine blade applications, requires 21.2 MJ/kg for conventional and as low as 10 MJ/kg for microwave-assisted processes [141, 144], with fibre strength retention ranging from 50-90% depending on process parameters [141]. However, pyrolysis is energy-intensive and often produces mixtures of oil and gas, limiting economic viability [144].
- **Chemical recycling**: This process can recover fibres with 85-99% of their original strength and enables the potential for closed-loop recycling if green solvents and mild conditions are employed [144]. The energy demand for chemical recycling is higher (63-91 MJ/kg) compared to mechanical methods but offers superior material recovery and circularity potentials [141].

For fibre-reinforced composites, the recovery of valuable reinforcement materials presents additional environmental benefits. Recycled carbon fibres obtained through optimised processes can maintain 70-75% of their original strength while reducing environmental impact by 30-50% compared to virgin fibre production [141].

A comparative LCA of recycling versus landfill scenarios for hemp/epoxy composites demonstrates significant environmental benefits across three damage categories: Human health (measured in Disability-Adjusted Life Years), Ecosystem Quality (measured as loss of species per year), and Resources (measured in MJ of additional energy demand) [142]. The recycling scenario shows notable reductions in all three categories, particularly in resource consumption. Recent LCA studies on closed-loop chemical recycling of carbon fibre/epoxy composites show that the global warming potential (GWP) for recycled carbon fibres can be reduced by 35-51% compared to virgin production, with cumulative energy demand reductions of 32-50% [144]. Open-loop recycling scenarios, where recovered fibres are downcycled into lower-value applications, show less favourable outcomes.

Conclusion

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Cured epoxy resins remain difficult to recycle because their permanent crosslinked networks cannot be remelted. Mechanical recycling generally produces lower-value fillers, while thermal and chemical routes can recover fibres or chemical fractions but may require substantial energy, solvents, catalysts, and emission controls. These limitations are most evident for large fibre-reinforced components, for which collection, separation, and quality-preserving recovery infrastructure remain underdeveloped.

The most promising pathway combines improved treatment of existing waste with design for circularity. Dynamic covalent networks and cleavable curing chemistry can enable reprocessing or controlled deconstruction, while carefully selected bio-based feedstocks can reduce dependence on fossil resources. These attributes must be assessed independently: renewable origin alone does not guarantee biodegradability or recyclability. For composites, process selection should also distinguish whether the intended product is recovered resin-derived chemicals, preserved fibres, or both.

Future work should prioritise pilot-scale validation on representative waste streams, solvent and catalyst recovery, product-quality specifications, transparent techno-economic and life-cycle assessment, and design-for-recycling standards. Collaboration among researchers, manufacturers, recyclers, and policymakers will be essential to convert laboratory advances into safe and economically credible closed-loop system.

Overall, scalable chemical and hybrid recycling, combined with epoxy networks engineered for repair, reprocessing, and selective deconstruction, can shift epoxy materials from persistent waste toward higher-value circular use without compromising their engineering performance.

Acknowledgement

This research was supported by the Trailblazer for Recycling and Clean Energy (TRaCE) Mobility Fellowship awarded to Dr. Rumana Hossain, in collaboration with Siemens Ltd.

Conflict of Interest Statement

Rumana Hossain received a Trailblazer for Recycling and Clean Energy (TRaCE) Mobility Fellowship in collaboration with Siemens Ltd. Brett Watson is an employee of Siemens Ltd. Veena Sahajwalla declares no competing interests.

The author Rumana Hossain is an Associate Editor of Cambridge Materials: Circularity, and Veena Sahajwalla is the Editor-in-Chief of Cambridge Materials: Circularity. Neither were involved in the editorial handling of this manuscript, or in the decision to publish. The peer review process was managed independently by the Associate Editor Kerry Kirwan.

The authors declare no other competing interests.

Data Availability Statement

No new experimental data were generated for this review article. The information supporting the literature, patent, and policy analyses was obtained from publicly available sources cited in the article. All relevant data are included within the article, its tables, and figures.

Author Contributions

Rumana Hossain: Conceptualisation, methodology, investigation, data curation, formal analysis, visualisation, writing—original draft, writing—review and editing, project administration, and funding acquisition. Brett Watson: Industry-focused interpretation, and

https://doi.org/10.1017/S2978168X26000040 Published online by Cambridge University Press

writing—review and editing. Veena Sahajwalla: writing—review and editing. All authors reviewed and approved the final manuscript.

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