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Cardanol Glycidyl Ether in Advanced Materials: Recent Progress, Synthetic Strategies, and Future Perspectives

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Abstract

Cardanol glycidyl ether (CGE), a bio-based precursor and epoxy derived product has been emerged as a promising sustainable alternative to conventional petroleum-based epoxy materials. Due to the presence of a phenolic hydroxyl group and an unsaturated aliphatic side chain, cardanol can be effectively undergoes glycidylation to produce reactive epoxy monomers that has excellent flexibility, hydrophobicity, low viscosity, and notably good chemical resistance. In recent years, CGE-based systems have attracted remarkable attention for applications in coatings, adhesives, composites, UV-curable materials, and high-performance thermosetting networks. The incorporation of CGE into polymer matrices enhances their toughness, thermal stability, corrosion resistance, and mechanical performance with the reduction in the brittleness of the polymer commonly associated with conventional epoxy resins. Likewise, the renewable origin and lower environmental impact of glycidylated cardanol contribute to the growing interest in sustainable polymer development. Recent studies have also explored its utilization in flame-retardant nanocomposites, hybrid materials, and advanced functional coatings for industrial applications. This review highlights the recent developments in the synthesis, modification, curing behavior, structure–property relationships, and emerging applications of CGE-based materials, together with the current and future prospects for their large-scale accumulation in advanced polymer engineering.

Keywords: Bio-based epoxy, cashew nut shell liquid, thermosetting polymers, sustainable coatings, Cardanol glycidyl ether

INTRODUCTION

The growing environmental concerns combined with the decrease in fossil fuel use, greenhouse gases emissions, and the raising usages of non-biodegradable polymeric materials have accelerated global research toward the development of sustainable and renewable polymeric materials. Conventional petroleum-derived polymers and thermosetting resins, although extensively utilized in coatings, adhesives, composites, electronics, and structural materials, were often combined with high carbon footprints and limited sustainability [1, 2]. At the same time, significant attention has been directed toward bio-based feedstocks capable of partially or completely replacing petrochemical precursors without compromising material performance. Among the numerous renewable resources investigated in recent years, Cardanol has emerged as one of the most promising naturally derived platform molecules for advanced polymer synthesis.

CGE is a phenolic resin synthesized after glycidylation (or epoxidation) of Cardanol a precursor obtained from cashew nut shell liquid (CNSL) which is a rich agro-industrial byproduct

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obtained during cashew processing (as shown in Figure 1). Structurally, CGE consists of a glycidyl ether group attached to the aromatic ring of the cardanol that already possess a long unsaturated hydrophobic aliphatic chain. This unique molecular architecture provides exceptional opportunities for chemical functionalization through reactions involving both the glycidyl group and the unsaturated side chain [3]. The presence of flexible long alkyl chain produces hydrophobicity, flexibility, low viscosity, and enhanced chemical resistance, making CGE highly attractive for the preparation of high-performance polymeric systems after different functionalization.

Among various cardanol derivatives, CGE has attracted a huge interest due to its capability to function as a renewable epoxy precursor for thermosetting and photocurable applications. Glycidylation of cardanol is achieved through the reaction with epichlorohydrin (as shown in Figure 2), resulting in the formation of epoxy-functionalized cardanol derivatives that possess improved reactivity and processability. Compared with conventional Bisphenol-A-based epoxy systems, glycidylated cardanol exhibits several advantageous characteristics, including lower brittleness, improved toughness, superior flexibility, enhanced hydrophobicity, and better corrosion resistance (as shown in Table 1). Also, the incorporation of renewable cardanol structures paves the way toward the reduced dependence on petroleum-based feedstocks and minimizing environmental impact.

Recent advancements in CGE chemistry have enabled the development of a various variety of functionalized materials including epoxy thermosets, UV-curable coatings, adhesives, nanocomposites, hybrid polymers, flame-retardant systems, and smart surface coatings. The tunable unsaturation within the side chain of the CGE further enables additional modifications such as acrylation, thiol–ene reactions, oxidative crosslinking, and incorporation into the multifunctional polymer networks. Also, CGE-based materials have shown promising thermal stability, dielectric behavior, anticorrosive performance, and mechanical durability for industrial applications in automotive, aerospace, marine, and electronic sectors. Diplomatics related to oxidative stability when subjecting in to exposure to UV (sunlight), curing kinetics (based on the curing agents), viscosity optimization (depends on the substrate), and balancing flexibility with thermal, electrical and mechanical performance needs continual investigation. Further researches are necessary to establish clear structure–property relationships and scalable green synthesis approaches for advancement in the industrial accumulation.

This review summarizes the recent developments in CGE-based polymers and materials, that focused on synthesis methodologies [4, 5], chemical modifications [6–8], curing behavior [9], and emerging applications. Also, a particular discussion on the recent advances in nanocomposites [10], UV-curable systems [11], flame-retardant materials, and sustainable high-performance coatings and future research directions for CGE-derived materials are majorly discussed.

Chemistry of Glycidylated Cardanol (CGE)

The structure of CGE consists an aromatic phenyl ring bearing an oxirane and a long unsaturated C_{15} aliphatic chain, combines rigid and flexible functionality, producing reactivity relatively equals to petroleum-based epoxies like DGEBA and DGEBF. The oxirane drives rapid nucleophilic ring-opening cures (amines, anhydrides, thiols, alcohols) and cationic polymerization, whereas, the unsaturated side chain enables secondary curing pathways (autoxidation, thiol–ene, radical grafting, hydrogenation). Compared with DGEBA and DGEBF, CGE networks typically show lower crosslink density and Tg but greater toughness, flexibility, and adhesion which is strongly determined by the curing behavior the curing agent utilized. CGE's low viscosity and multifunctionality make it valuable as both precursor and reactive diluent in coatings, adhesives, UV-curable systems, and composites. Although the trade-offs include reduced thermal resistance and oxidative sensitivity, issues commonly mitigated by hybrid formulations, nanofillers and dual-curing strategies.

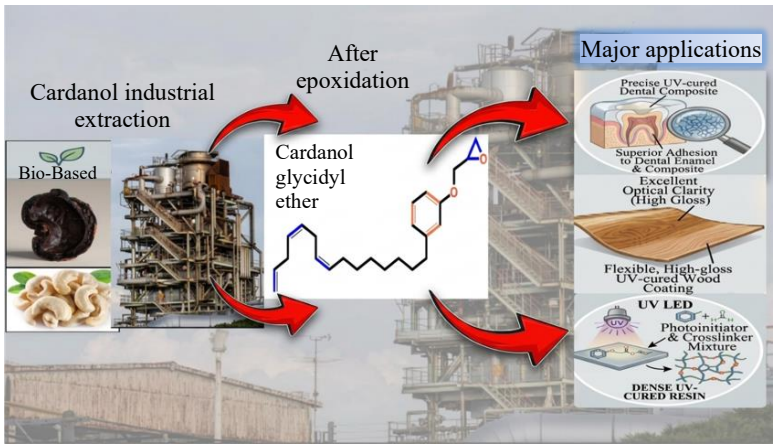

Figure 1. Synthetic scheme for the preparation of CGE and its applications.

Table 1. Technical comparison between CGE and other petroleum-based competitors.

Property	Glycidylated cardanol	DGEBA/DGEBF
Feedstock origin	Renewable, bio-based; derived from cashew nut shell liquid	Petroleum-derived
Viscosity	Lower	Higher
Flexibility	High	Moderate
Crosslink density	Lower	Higher
Thermal resistance	Moderate	High
Toughness	Excellent	Moderate
Hydrophobicity	High	Moderate
UV stability	Improved	Moderate
Brittleness	Low	Higher
Sustainability	Excellent	Limited
Best suited for	Flexible, tough, hydrophobic, and sustainable epoxy systems	High-strength, high-stiffness, and high-temperature applications

Table 2. CGE reactivity toward various curing agents.

Curing Agent	Mechanism	Advantages	Limitations
Primary amines	Nucleophilic epoxy ring opening	Fast curing and strong adhesion	Lower thermal resistance
Aromatic amines	Step-growth polymerization	High Tg and thermal stability	Brittleness
Anhydrides	Esterification after epoxy opening	Excellent electrical properties	Requires catalysts
Thiols	Thiol–epoxy click reaction	Rapid room-temperature curing	Odor sensitivity
Phenols	Etherification	Chemical resistance	Slow reaction rate
Carboxylic acids	Ester formation	Tough networks	Higher curing temperature

Zhang, J.; Zhang, Z in 2025 and Jahan, A. Masood, S.; Zafar, F in 2024, reported that amine curing generally proceeds rapidly at moderate temperatures and produces flexible thermosets with high adhesion properties [12–14]. Also, the aliphatic amines yield softer and more ductile materials, whereas aromatic amines generate thermally stable but relatively rigid networks was reported by *Jilani, W.; Gouadria, S.; Bouzidi, A* in 2023 [12, 15]. Cycloaliphatic amines often provide an optimal balance between toughness and thermal stability [16]. The flexible aliphatic side chain of cardanol decreases packing efficiency within the polymer matrix and increases free volume, thereby reducing internal stress during curing and minimizing brittleness. This behavior is considered as an advantageous property in coatings and structural adhesives, where flexibility and crack resistance are critical with some of the disadvantages (as shown in the Table 2). Among these curing pathways, anhydride curing has received notable attention because it produces thermally stable polyester-type

networks with improved dielectric properties and low shrinkage. The mechanism generally involves catalyst-assisted opening of the epoxide ring followed by reaction with cyclic anhydrides to generate ester linkages. Imidazoles, tertiary amines, and Lewis acids are commonly used catalysts for such reactions was reported by *Hansen, T. et.al.* [17] Thermosets prepared through anhydride curing exhibits enhanced chemical resistance and dimensional stability compared to amine-cured systems [1].

Another important aspect of CGE chemistry is the presence of unsaturation within the C_{15} side chain. Depending on the source and processing conditions, the precursor Cardanol might be containing monoene, diene, to triene structures [18]. This unsaturation provides additional reactive sites capable of participating in radical-mediated curing reactions i.e., UV-curable reactions. *Wieszczycka, K.; Staszak, K et.al.; Varganici, C.-D.; Rosu, L.; Rosu, et.al.; and Pustahija, L, et. Al* were reported Thiol–ene click reactions [19] are most attractive in these cases because they proceed instantly under UV irradiation permitting efficient surface functionalization [20–23]. Relatively similar to these researches, *Maillot, B. and coworkers* reported in their recent work in 2024 radical grafting reaction (RGR) [24] enables the incorporation of acrylic monomers, vinyl compounds, and functional oligomers into cardanol-based systems. These types of modifications expand the applicability of CGE in UV-curable coatings, hybrid thermosets, and smart materials that were utilized across the applications.

Cardanol glycidyl ether (CGE) undergoes conventional nucleophilic epoxy curing with aliphatic and aromatic amines or anhydrides and can also participate in cationic ring-opening polymerization (CROP) initiated by Lewis acids such as BF_3-etherate or photo-generated Brønsted acids derived from triarylsulfonium and diaryliodonium salts [25–29]. Compared with free-radical photopolymerization, cationic curing offers several advantages, including negligible oxygen inhibition, lower volumetric shrinkage, dark-curing capability, and improved adhesion to metallic and polymeric substrates due to the highly polar polyether network formed during epoxy polymerization [25, 28, 29]. The unsaturated C15 aliphatic side chain of CGE further imparts unique chemical reactivity through autoxidation at allylic positions, where atmospheric oxygen generates hydroperoxide intermediates that subsequently decompose into radical species, promoting oxidative crosslinking. Although this air-drying behavior is advantageous for coating applications, prolonged oxidation may result in yellowing and embrittlement during long-term storage or service [26, 27]. Consequently, partial or complete hydrogenation of the side chain has been employed to suppress oxidative degradation while retaining the flexibility and hydrophobicity imparted by the long alkyl chain [26, 27].

The low viscosity and of CGE makes it an effective bio-based reactive diluent in solvent-free and low-VOC epoxy formulations, reducing processing viscosity without sacrificing network integrity, thereby minimizing the requirement for volatile organic solvents [27, 30]. During epoxy curing, hydroxyl groups generated by epoxide ring opening enhance intermolecular hydrogen bonding, improve filler dispersion and interfacial adhesion, and provide reactive sites for secondary reactions such as urethane formation or esterification, facilitating the fabrication of hybrid thermosetting networks and interpenetrating polymer networks (IPNs) [27, 29].Nevertheless, the flexible aliphatic side chain decreases chain packing efficiency and generally lowers the glass transition temperature (Tg) and modulus compared with conventional aromatic epoxy systems such as DGEBA, while steric hindrance surrounding the glycidyl functionality may reduce cure kinetics [27, 30]. To compensate for these limitations, hybrid formulations incorporating CGE with DGEBA or multifunctional epoxy resins, the use of rigid aromatic curing agents, and dual-curing strategies combining cationic and radical polymerization have been widely investigated to improve crosslink density, thermal stability, and mechanical performance [26–29, 31].

Incorporation of nanoscale reinforcements including graphene oxide, silica nanoparticles, nanoclays, cellulose nanofibers, carbon nanotubes, and mixed metal oxide fillers based on Zn, Ti, Sb,

and Al has been demonstrated to significantly improve stiffness, thermal resistance, char yield, and flame retardancy while maintaining fracture toughness when homogeneous dispersion is achieved [32, 33]. Furthermore, acrylation of hydroxylated epoxy intermediates produces epoxy acrylates suitable for rapid UV photopolymerization, thereby extending the application of CGE to UV-curable coatings, inks, adhesives, and additive manufacturing resins [25, 27]. Collectively, these modification strategies enable precise tailoring of the mechanical, thermal, and chemical properties of CGE-based thermosets for diverse engineering applications. Consequently, CGE has emerged as an attractive bio-based platform chemical for coatings, adhesives, composites, flame-retardant materials, and advanced photopolymer systems. Continued developments in controlled hydrogenation, molecular hybridization, optimized curing methodologies, and nanoscale reinforcement are expected to further reconcile its excellent processability and sustainability with the increasing demand for higher glass transition temperatures, enhanced oxidative stability, faster curing kinetics, and superior long-term performance [25–30, 32, 33]

Various Chemical Modifications on CGE

Among the various chemically modified derivatives of Cardanol, CGE has emerged as one of the most important renewable epoxy intermediates for advanced polymeric materials. The increasing demand for sustainable thermosetting systems, coupled with environmental concerns associated with petroleum-derived epoxy resins, has significantly accelerated research interest in cardanol-based glycidyl ethers. In the presence of a phenolic hydroxyl group and an unsaturated C_{15} aliphatic side chain, cardanol serves as an ideal precursor for the synthesis of flexible and hydrophobic epoxy materials with tunable physicochemical properties [10, 34] (as shown in Table 3).

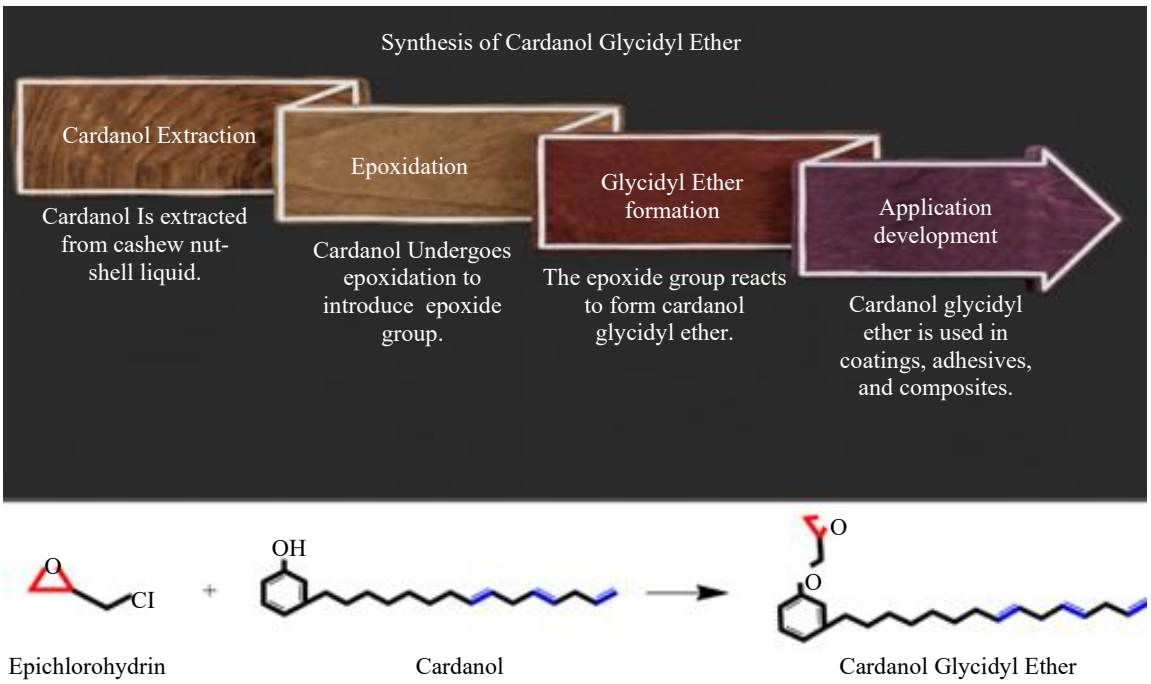

Figure 2. Synthesis of cardanol glycidyl ether.

Table 3. Side-chain reactivity pathways of CGE.

Reaction type	Reactive site	Typical reagents	Resulting functionality
Thiol–ene reaction	C=C bond	Thiols and photoinitiators	Sulfur-functional polymers
Epoxidation	Double bond	Peracids	Additional epoxy groups
Hydrogenation	Unsaturation	H2/Pd catalysts	Improved oxidative stability
Radical grafting	Alkene functionality	Acrylates and peroxides	Hybrid polymer systems
Autoxidation	Unsaturated chain	Atmospheric oxygen	Oxidative crosslinking

The epoxidation mechanism is the core of the material properties of CGE-based systems. The oxirane moiety enables participation in various curing reactions including amines, anhydrides, thiols, acids, and phenolic hardeners. Also, it has been extensively employed as a bio-based reactive diluent, flexibilizer, and epoxy precursor in thermosetting formulations. The glycidylation reaction can be represented schematically as:

Comparative to conventional synthetic epoxy resins such as DGEBA and DGEBF, CGE exhibits lower viscosity and enhanced flexibility due to the presence of long aliphatic side chain. These characteristics improve processability, filler dispersion, and stress relaxation behavior during curing with those external curing agents. The unsaturated side chain of CGE provides more advanced opportunities for secondary chemical modifications. Epoxidation of the double bonds present in the side chain can generate multifunctional epoxy systems with increased epoxy functionality and higher crosslink density. These side-chain epoxidized derivatives often demonstrate enhanced thermal stability, chemical resistance, and superior mechanical integrity due to their higher crosslink density. The degree of unsaturation in CGE moreover, influences the reactivity and final network architecture of the cured system [35]. The epoxy value and oxirane oxygen content are critical parameters that governs the curing behavior and crosslinking efficiency of CGE systems [36]. Higher epoxy functionality generally results in increased crosslink density, leading to improved thermal resistance and mechanical strength. However, the more crosslinking may result in reduced flexibility and toughness. Therefore, optimization of epoxy content remains essential for balancing rigidity and ductility in advanced applications. The epoxy value can be obtained by volumetric analysis [36].

Epoxy Value = Number of epoxy equivalents/Mass of resin (kg)

CGE derivatives have been widely explored in coatings and anticorrosive materials due to their excellent hydrophobicity and chemical resistance after various modifications with various catalysts or curing agents (as shown in the Table 2). The long aliphatic chain acts as an effective moisture barrier, reducing water permeability and improving anti-corrosive and strong adhesion performance on metallic as well as non-metallic substrates. Several studies have demonstrated that epoxy coatings containing CGE has improved salt-spray resistance, adhesion strength, and flexibility compared to fully petroleum-based systems. Also, the incorporation of cardanol-derived epoxies frequently lowers volatile organic compound emissions and enhances sustainability.

APPLICATIONS OF CGE IN VARIOUS FIELDS

CGE in nano Applications

Yadav, V., et. al., and Kumari, S.; Saini, A., et. al., reported an important research direction involves the accumulation of CGE in nanocomposite formulations [37]. The reactive epoxide moiety facilitates strong interfacial interactions with inorganic fillers like metal oxides, silica nanoparticles, nanoclays, graphene oxide, carbon nanotubes, and mixed metal oxides [38]. These hybrid systems often displayed the enhancement in thermal conductivity, flame retardancy, and mechanical reinforcement, also acted as thermal and electrical barriers. In such a case, the synergistic interactions between cardanol-based epoxy matrices and phosphorus- or metal-containing additives have shown promising results in flame-retardant applications and are equivalent to several lifesaving applications. The flexibility imparted by the aliphatic side chain also makes CGE attractive for toughening brittle epoxy systems. Due to the reduced impact strength and strong flexibility, the addition of CGE in other polymer networks notably increases their fracture toughness and improves elongation at break by inducing high internal stress without severely compromising thermal stability.

CGE in Photo Applications

He, Q.; Hu, L.; Huang, Y.; Huang, T. et. al., reported on CGE's role in UV-curable systems, CGE commonly functions as a reactive diluent, flexibilizer, or co-reactive modifier [39]. The epoxy functionality participates in cationic photopolymerization, on the otherhand the phenolic structure and unsaturated hydrocarbon chain contribute to improved compatibility with other external oligomers and polymer matrices. Compared with conventional petroleum-derived epoxy diluents, CGE offers lower viscosity and enhanced flow behavior, which facilitates processing and reduces the overall

volatile organic compound (VOC) content of the formulation. Also, the reports explained that, the incorporation of CGE also improves substrate wetting and interfacial adhesion due to its amphiphilic molecular architecture. Photo-curable coatings containing CGE contains a wide variety of advanced properties that includes reduced brittleness, improved impact resistance, and better scratch resistance. In addition, the long alkyl C_{15} chain originated from cardanol acts as an internal plasticizing segment that lowers the internal stress generated during rapid UV curing upon reaction with various photo initiators like TPO had been reported in *Gartili, A., et. al., review reported in 2025 [*40].

Protective and Anticorrosive Coatings

Protective coatings represent one of the most commercially promising application areas for CGE [14]. The hydrophobic aliphatic chain present in cardanol enhances moisture resistance and decreases water permeability within cured epoxy coatings. Consequently, glycidylated cardanol-based coatings have demonstrated exceptional anticorrosive behavior on metallic substrates exposed to humid or saline environments. Recent developments have focused on incorporating nanofillers such as graphene oxide, nano-silica, layered clay, zinc oxide, and mixed metal oxides into glycidylated cardanol matrices to improve barrier properties and corrosion resistance [41]. The synergistic interaction between the hydrophobic organic phase and impermeable nanofillers creates highly tortuous diffusion pathways that inhibit the penetration of corrosive species [42]. Also, glycidylated cardanol coatings show excellent adhesion to steel and aluminium surfaces owing to the polar epoxy groups capable of forming strong interfacial interactions. Several studies have also reported improved chemical resistance against acids, alkalis, and solvents compared with conventional alkyd and polyester coatings.

Flame-Retardant Epoxy Systems

The development of flame-retardant CGE -based polymers has recently been integrated into flame-retardant epoxy systems [43] through the incorporation of phosphorus-, silicon-, nitrogen-, and metal-containing additives [44–47]. Recently, several researchers *Yuan, Y., et. al., Wang, K., et. al.,* and their co-workers have designed multifunctional glycidylated cardanol derivatives containing phosphorus groups capable of promoting char formation during thermal degradation [48]. The long aliphatic chain of cardanol contributes to the formation of compact carbonaceous char layers that act as thermal barriers during combustion. The aromatic structure supports condensed-phase flame-retardant mechanisms by improving carbon yield. Recent nanocomposite approaches involving cerium-based mixed metal oxides, layered double hydroxides, montmorillonite, and graphene derivatives have shown remarkable reductions in heat release rate and smoke generation [49]. These hybrid flame-retardant systems demonstrate the potential of glycidylated cardanol in high-performance structural composites and electronic encapsulation materials requiring enhanced fire safety [50].

Limitations of CGE

Cardanol glycidyl ether (CGE) offers renewable, multifunctional epoxy functionality but has some major to minor limitations for high-end engineering and UV-curable applications where it is supposed to be applied. CGE is typically monofunctional that yields relatively lower crosslink density than other commercial resins like DGEBA/DGEBF or novolac epoxies which results in reduced hardness, modulus, and thermal resistance. However, these characteristics are the problematic properties for structural coatings and high-temperature utilizations. Its long unsaturated aliphatic side chain improves toughness but lowers the rigidity and glass transition temperature (Tg) of the composite, causing poorer dimensional stability, adhesive strength and load-bearing performance [35]. Also, in cationic UV curing the bulky hydrophobic chain slows down the epoxy ring-opening and cause incomplete cure under low UV or insufficient photoinitiator, leaving residual epoxies [26, 51]. Also, the unsaturation also lowers thermal/oxidative stability, promoting yellowing and property loss without stabilizers. In nanocomposites excess CGE can reduce stiffness and barrier properties, and cause phase separation or poor filler dispersion if polarity is mismatched which complicates the viscosity, curing, and reproducibility of the resins. Finally, the commercialization of CGE faces

challenge in cost of purification so research focuses on hybrid formulations using CGE in limited roles so as to reduce the consumption of synthetic polymers.

CONCLUSION

Upon reviewing recently, the CGE epoxy precursor came a long way in the focus of researchers. Offering good toughness, flexibility, hydrophobicity, low viscosity, and good processability due to the presence of aromatic phenolic core and long aliphatic side chain CGE playing vital role in the reduction of synthetic polymers. These properties outperforms many petroleum-based resins like DGEBA and DGEBF in various fields like moisture resistance, UV-resistance and reduced brittleness. Recently, from 2020-2026, the advancements in glycidylation and structural modification has been widely expanded in the applications of thermosets, coatings, adhesives, nanocomposites, flame-retardant and UV-curable systems, and electronics. Compatibility of CGE, with nanofillers like graphene, mixed metal oxides, phosphorus-based additives, and bio-reinforcements enables multifunctional hybrids with improved thermal stability, mechanical strength and corrosion resistance. Challenges include feedstock variability, limited epoxy functionality, flexibility and thermal resistance, and reliance on toxic reactants only when CGE is set to be compared with pure synthetic polymers. Key future directions should be focused on green synthesis, fully bio-based curing agents, advanced molecular design, free compatibility and integration into bio manufacturing, self-healing coatings, conducting polymers and in energy-storage devices to boost commercial adoption. Finally, the present and upcoming researchers might consider and look forward to a cost-effective formulation with bio-based and sustainable epoxy resins with CGE after overcoming its limitations, with their curing agents that are totally bio based are the futuristic research area to make our Earth a green hub.

Declarations

We declare that I have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

We declare that both the authors contributed equally to this article.

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Conflict of Interest

The authors declare there is no conflict of interest.

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