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**Review Article**

# Epoxy resins: Recent advances, challenges and future perspectives

**Ritika Pandey[1], Darshan Sharma[1,*], Rakesh Mani Mishra[2]**

[1]Department of Physics, Harishchandra Post Graduate College, Varanasi-221001, U.P., India
[2]Department of Chemistry, Harishchandra Post Graduate College, Varanasi-221001, U.P., India
[*]Corresponding author, E-mail: dsharma@hcpgcollege.edu.in

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**ABSTRACT**
Epoxy resins are high-performance thermosetting polymers that are widely used in various industrial sectors, including aerospace, automotive, electronics, and construction. Epoxy resin is highly appreciated for its excellent mechanical strength, strong thermal stability, good chemical resistance and excellent adhesion properties. This review provides an overview of the fundamental chemistry of epoxy resins and their synthesis routes, including conventional systems such as diglycidyl ether of bisphenol A (DGEBA), Novolac epoxies, and cycloaliphatic epoxies. Cross-linking occurs during curing and generates a 3D network structure that strongly determines the final properties of the materials. The development of advanced materials engineering places substantial emphasis on the crucial role of epoxy resins in industrial applications and day-to-day life. Recent developments have primarily focused on improving the performance of the materials. The development of bio-based epoxies, self-healing systems, and fibre-reinforced epoxy materials is illustrated. The primary challenges of the epoxy system include brittleness, environmental concerns and recyclability issues. To overcome these challenges, several strategies exist, including toughening approaches and sustainable composite design. Future research aims to develop multifunctional epoxy composites for next-generation functional materials that offer recyclability and sustainability, as well as environmentally friendly, recyclable thermoset materials.

## 1. Introduction

The term epoxy refers to a thermoplastic system used to describe the uncross-linked state that undergoes curing to form a highly cross-linked network [1]. Epoxy resins are classified as thermosetting materials due to their excellent mechanical strength, strong adhesion, good chemical resistance and excellent thermal stability [2].

Epoxy resins have a long and expanding history back to the late 19th century, as early as 1863. Early research in pioneering chemistry began in the early 20th century, while large-scale epoxy technology and commercial development also emerged in the mid-century [1]. During the late 1930s and early 1940s, Pierre Catan and Dr Sylvan O. Greenlee synthesised diglycidyl ether of bisphenol A (DGEBA) by reacting bisphenol A (BPA) with epichlorohydrin, and this later became the most widely used commercial epoxy resin [1].

In 1938, Pierre Catan, working in Zurich, developed this thermoset resin, obtained by reacting phthalic anhydride. In the early stages of his research, he explored applications such as dental fixtures and casings [1, 3].

At the same time in the U.S., Sylvan O. Greenlee synthesised a similar BPA with a higher molecular weight while working with Devoe and Raynolds.[1]In the early 1940s, Daniel Swen introduced an alternative method for producing epoxy compounds by epoxidising olefins with peroxy acids. These techniques are used to manufacture epoxy compounds containing stabilisers and plasticisers [1]. This was the early era where epoxy resin became the most prominent thermoset polymer [4].

In 1947, industrial use expanded rapidly [1]. Now, epoxy resins are widely employed in surface coatings, adhesives, composites, electrical encapsulation and structural materials [1, 4]. The epoxy resin market continues to grow steadily, with demand valued at $7.2 billion in 2018, and is expected to grow by up to 6% annually [1].

Resins play a crucial role in achieving high mechanical properties, durability, and structural stability through the combination of reinforcing fibre and matrix. Modern engineering and industrial applications demand lightweight, rigid materials, which drive research into advanced resin systems, leading to the optimisation of corrosion resistance, mechanical properties, and chemical durability [5].

Since the late 1930s, epoxy resin has become dominant in industrial sectors and many others. Here are some timelines based on the above data.

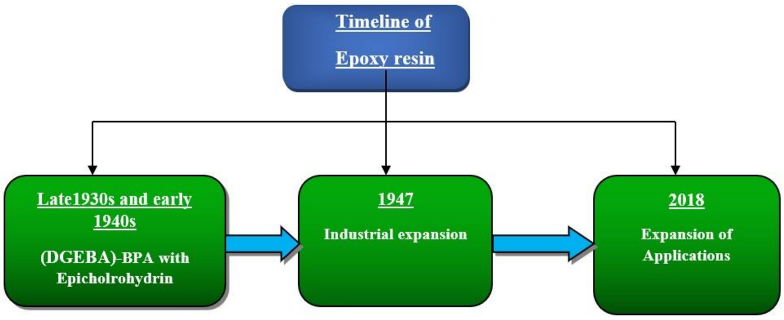


**Figure 1:** Timeline of epoxy resins [1].

## 2. Fundamentals of epoxy resins

The term epoxy refers to a thermoplastic system, used to describe the uncross-linked state, which undergoes the curing process to form a highly cross-linked network [1]. An epoxy resin contains one oxygen atom and two carbon atoms, as illustrated in Figure 2 [3].

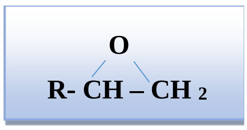


**Figure 2:** Structure of the epoxy functional group [3].

This is a three-dimensional network (also called three-membered cyclic rings). This ring is often called the α-epoxy or oxirane ring. Ethylene oxide is an example of this type of resin [1].

During curing, the reactive epoxide groups undergo chemical reactions, so the final materials no longer contain any free epoxy groups. The cured resin materials are called as epoxy resins [3]. Epoxy Resin is one of the most important classes of polymers for modern industry applications [1]. Epoxy resin is defined as a compound that usually contains more than one epoxide (oxirane) group per molecule. Epoxies exhibit significant ring strain in three–membered rings, which makes them highly reactive [4].

## 3. Need for epoxy resins

The epoxy resins are well known based on their mechanical strength, excellent chemical resistance and high electrical insulation properties [6, 7]. Their properties depend on the specific combination of an epoxy resin and its curing system [6]. Over the past few years, environmental protection and resource conservation have drawn attention towards the development of degradable epoxy resins [7].

## 4. Types of epoxy resin

**Diglycidyl Ether of bisphenol A resins:** The DGEBA constitutes one of the most common types of epoxy resins. It is produced by the reaction of epichlorohydrin and bisphenol-A, as shown in Figure 2**.** It was also the first commercial epoxy resin. The commercial grade of DGEBA has a molecular weight of about 380, whereas the pure versions (n≈0) have a molecular weight typically less than 344. Owing to their high purity, they may undergo crystallisation during storage [1].

High-viscosity DGEBA provides a faster curing reaction than standard resins [1]. DGEBA exhibits favourable chemical resistance, good thermal properties, and high adhesion strength to a broad range of substrates [8]. This reaction was carried out in the presence of sodium hydroxide, one of the most important catalysts used in the manufacture of epoxy resins [9]. DGEBA represents the most common type of epoxy resin, accounting for nearly 70% of total epoxy usage [10]. The DGEBA is widely used in the electronics, automotive, aerospace, and coatings industries [11]. The length of the polymer chains strongly influences their properties, and it is assumed to meet nearly 75% of industrial and household requirements [9]. DGEBA is the basic type of epoxies [12].

***Problem:*** The cured DGEBA shows a lower toughness due to the presence of aromatic ring structures [8].

***Solution:*** The brittleness of DGEBA is reduced by the incorporation of elastomers, thermosetting modifiers, and thermoplastic polymers, which help improve its toughness [8].

**Novolac Resins:** Phenol-formaldehyde resins were used to form this type of resin, as shown in Figure 3 [1]. The diglycidyl ether of novolac has gained commercial importance due to its higher functionality compared with other epoxy systems [1]. It is used in applications such as powder coatings for corrosion-resistant pipelines [3], as shown in Table 1**.** The epoxide group present in this resin leads to the formation of a more highly crosslinked structure. As a result, novolac resin possesses high thermal and chemical resistance, which makes it highly suitable for composites, adhesives, and matrix materials [9].

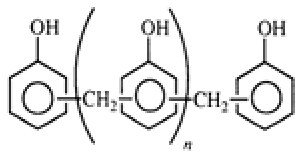


**Figure 3:** Structure of Novolac Resins [3].

**Cycloaliphatic Epoxy:** The cycloaliphatic epoxies exhibit excellent UV(Ultraviolet) resistance and superior dielectric properties, which make them highly suitable for electrical encapsulation applications [3]. It is commercially used in the electronics and electrical industries because of its low viscosity and minimal electrical loss [1].

**Bisphenol A:** 7p- Hydroxyphenyl propane, commonly known as bisphenol-A (BPA), is formed by the reaction of acetone and phenol in the presence of acid catalysts such as 75% of sulphuric acid or dry hydrogen, as shown in Figure 4 [3]. Worldwide, BPA is considered among the most widely manufactured chemicals. Each year, over 4 million tonnes are released into the environment [13].

***Negative impact:*** The negative impact of BPA on various human health-related concerns (such as effects on the immune and reproductive systems). In addition, it also possesses environmental risks [13].

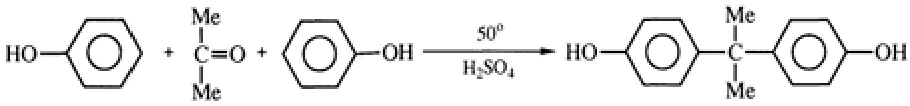

**Figure 4:** Synthesis of Bisphenol-A [3].

**Table 1:** Types of Epoxy resins with their applications.

| Resins | Applications | References |
|---|---|---|
| DGEBA | Coatings, Metal furniture, Finishes, castings applications, Flooring, Adhesives, composites. | [1] |
| Cycloaliphatic | Electrical properties, casting resins, and protective coatings: outdoor ageing due to a good UV absorber. | [3, 9] |
| Novolac epoxies | Powder coatings applications and moulding compounds | [3, 14] |

Recently, researchers have been focusing on epoxidised plant oils and fatty acids as environmentally friendly alternatives because they exhibit thermal characteristics similar to those of commercial DGEBA-based epoxy resins [13]. Nearly 90% of global epoxy resin production originates from the reaction of BPA and epichlorohydrin [6, 12, 13].
For a better understanding of these types of epoxy resin, which depend either on their chemical structure or on their performance. Table 1 gives a brief review of various types of epoxy resins and their applications in other sectors.

## 5. Curing agents and hardeners

Epoxy resins are formed when epoxy monomers undergo a reaction with curing agents that contain active hydrogen atoms, such as amines, through cross-linking mechanism [15].

1. Amines can be classified as primary, secondary and tertiary [1].
2. Primary amines react with epoxide groups through nucleophilic attack, to form secondary alcohols and lead to the formation of a 3D cross-linked network [3]. Secondary amines can further react with another epoxy group to produce tertiary amines [1].
3. Aromatic amines are used to improve the chemical resistance and extend pot life, but generally require heat for the curing process [1].
4. Cycloaliphatic amines provide higher heat distortion temperature (HDT) as compared to aliphatic amines. It provides high electrical performance and good thermal stability [1, 16].
5. Lewis's acid possesses empty orbital's in their outer atomic shells [1].
6. Curing agents are utilised for the modification of surface and functional procedures [14].

Curing agents, also known as hardeners or cross-linkers, convert epoxy monomers into thermosetting networks, and the resulting cross-linking structures affect the properties of the cured materials [12]. A dual curing system allows better control over the curing rate of epoxy resin and design the final product through two different curing systems operating with different reaction conditions [17].

## 6. Curing mechanisms and the effect of crosslinking density

In most epoxy systems, cross-linking generally occurs without affecting the epoxide conversion rate. It's led to the development of a three-dimensional network and minimises the chain segment mobility.[1]. The curing process involves the ring-opening polymerisation of the epoxide group, producing a hydroxyl group that can increase cross-linking. In the resin-to-hardener ratio, epoxy formulations require a higher amount of curing agents than polyester or vinyl ester systems [13]. The curing of epoxy involves a complex chemical reaction that transitions the material from a liquid to a solid-state network [18]. Cured epoxy resin materials exhibit a highly cross-linked amorphous structure [19]. Epoxy resins are primarily generated by a chemical reaction between epoxy compounds and curing agents (hardeners) [1, 16].

The curing agent plays a crucial role in determining the reaction rate, curing schedule, and resulting material characteristics. When epoxy reacts with the curing agent, cross-linked epoxy is formed [14]. Due to their 3D cross-linked structure, epoxy resins exhibit outstanding properties, including mechanical strength, excellent dielectric performance, and corrosion resistance.[7]The study investigates the influence of crosslink density on the mechanical and thermal stability of a new vitrimer, thereby supporting the development of bio-based and recycled resins [20].

## 7. Present status of Epoxy Resin

This section discusses the current global status of epoxy resins.

Epoxy resin has achieved substantial commercial importance due to its formulation techniques and diverse properties [1]. The concept of circular economy is based on reusing, repairing and recycling products, which supports economic growth by enhancing resource efficiency and minimising environmental harm. It aims to support the growth of the circular economy by increasing resource productivity and decoupling economic development from excessive resource consumption and environmental degradation. Circular economy is a fundamental concept that refers to an industrial system designed to be restored and regenerated in nature [21].

The material cycle in a circular economy growth is classified into two types:

**The biological cycle:** In this process, materials are naturally reverted into the biosphere without causing any negative impacts on the environment [21].

**The technical cycle:** In this cycle, materials are reused efficiently and without entering the biosphere [21].

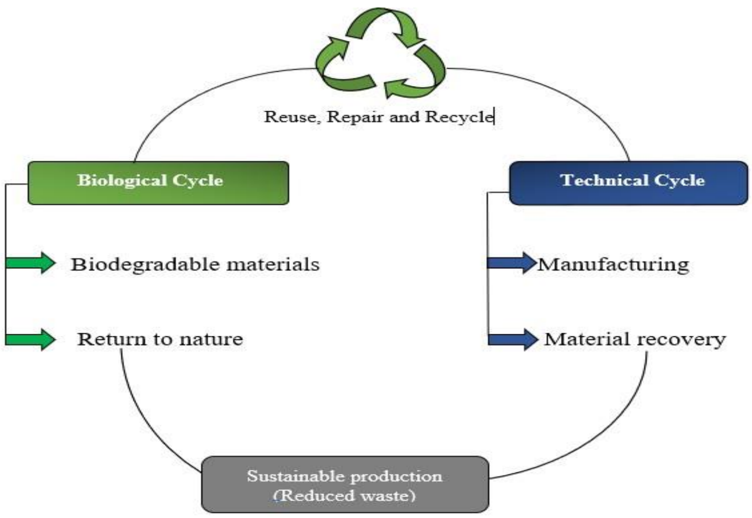


**Figure 5:** Circular economy approach for epoxy resins (reuse, repair, and recycling) [21].

The above Figure 5 illustrates the conceptual framework of the circular economy for the biological and technical cycles of epoxy resin, including reuse, repair, recycling, and material recovery, without any environmental concerns [21]. This model relies on large quantities of inexpensive, readily accessible raw materials and energy. This model promotes a pattern in which consumers generally replace with a new one [21].

Epoxy-based composite products currently play an important role in promoting the circular economy across various sectors [22].

In recent years, publications on epoxy nanocomposites have shown steady growth from 2016 to 2020. This indicates the increasing demand for nanofillers to reinforce epoxy systems [2].

## 8. Fast-growing research areas

In recent times, there have been several rapid developments in epoxy research and in the enhancement of epoxy materials.

(a) The high-strength composites and their role lead to the development of industrial applications [5].
(b) Epoxies lead to the development in various industrial and technological sectors [5].
(c) It largely focused on the materials properties and their fabrication approach [5].
(d) The study focuses on various resin systems for development and their effective properties [5]
(e) The demand for lightweight materials leads to the development of advanced formulations with their improved properties, such as thermal, mechanical, and chemical, respectively [5].

## 9. Underexposed areas

There remain key gaps, which are shown below.

(a) One of the gaps of epoxy resins is the deficiency in their recyclability.
(b) Another gap was the toughening and fibre-reinforced improvement.
(c) Making of bio-based materials that are eco-friendly.
(d) Environmental degradation is also being studied.
(e) High temperature, mainly 300°C, epoxy resin still needs to be developed [22].
(f) The sustainability or hybrid resin is still underexposed [5].

## 10. Market growth of epoxy at the global level

The global epoxy market continues to grow steadily.

(a) Due to its outstanding properties, epoxy resin has become dominant in the market. Epoxy Resins have become highly in demand for various applications, such as electrical applications, coatings, flooring, decorative items, and more.
(b) Many countries are higher in terms of production of epoxy resins and in terms of bio-based epoxies.
(c) The market of coatings, aerospace, automobiles and electrical applications has extensively increased over the years.
(d) It is assumed that in a few years, the epoxy market will become highly demanded at the global level.
(e) Further research is needed on the applications, including long-term performance and eco- friendly impacts [5].

## 11. Threats

(a) Collecting and transporting of epoxy waste is still considered a challenging process in the development of the circular economy [21].
(b) High cost for the recycling process shows a barrier to the circular economy growth [21].
(c) Upgradations of industrial processes for waste recycling can be challenging because they require technological and financial investments [21].

Epoxy resins have several remarkable properties (such as strong adhesion, high thermal stability, and corrosion and chemical resistance), which make them widely used in adhesive formulations and high-performance coating systems. Worldwide, 41% of liquid epoxy resins are utilised in coating applications, 31% are for adhesive products, and the remaining 28% are applied across various sectors, as shown in Figure 6) [23].

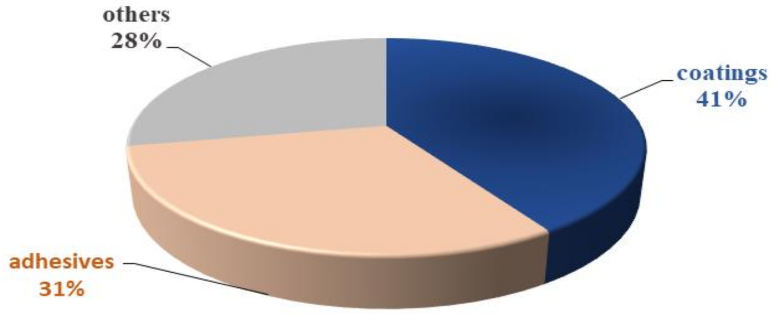


**Figure 6:** Distributions of epoxy resin in the current market [23].

## 12. Properties of Epoxy Resins

Depending on their unique properties, epoxy resins are utilised for commercial and industrial purposes.

***Physical Properties:*** Depending upon their physical properties, the epoxy resin becomes extremely flexible and possesses high strength [17]. The cured epoxy resin demonstrates low shrinkage and high strength [4, 24].

***Electrical Properties:*** Depending upon their electrical properties, they are highly used for coatings and electrical encapsulation components [3]. It shows high electrical insulation [3, 25].

***Thermal Properties:*** Depending upon its thermal properties, it possesses high thermal resistance[17]The addition of fillers allows for the modification of the epoxy resin's thermal properties [3].

***Mechanical Properties:*** Depending on its mechanical properties, it shows high strength and durability [17]. Cured epoxy possesses high mechanical strength [4].

The above information outlines the various properties of epoxy resins. Due to their properties, they are widely used in industrial and commercial applications.

## 13. Applications

Due to its vast development of epoxy resins and outstanding properties, it is widely used in various sectors:

***Aircraft and Aerospace Industry:*** It is used in the structure of aerospace because of its high strength-to-weight ratio and excellent adhesions [1]. It is also used in aeronautics systems because of its unique properties and minimal curing shrinkage [25]. Resin enhanced the mechanical performance and fuel efficiency in aerospace structures [5].

***Electronics:*** Space exploration technologies and high electrical insulation also use epoxy composites [1, 9].

***Automotive Industry:*** This industry utilises it for protective surface coatings and structural adhesives, especially used in primers and industrial maintenance paints [1, 13]. In addition, epoxy-based materials are commonly used in automobiles for power transmission, drive shafts, door panels, and seat backs [26]. Epoxy resin is used in the automotive industry to reduce weight and enhance vehicle safety [5].

***Construction:*** It is commonly used for chemically resistant industrial flooring and decorative items [1].

***Marine Applications:*** Epoxy resin possesses high wear resistance and mould resistance, which makes it highly suitable for marine systems, food, and the pharmaceutical industry [21].

Epoxy resin is widely used across various sectors, including the automotive, aerospace, chemical, electronics, and coatings industries [6].

## 14. Recent advances

***Fracture Toughness:*** Fracture Toughening is the ability of a material to resist crack formation by absorbing energy at the time of deformation [27]. Due to its structure and high cross-link density, it may show low toughness. The fillers are used to improve the toughness of epoxy resins [28]. The lightweight molecular structure is used in polymeric composites to improve the toughness [16, 28]. The higher the cross-linking, the lower the toughening [27]. To improve this toughness, various common approaches are discussed in Figure 7 below [4, 16].

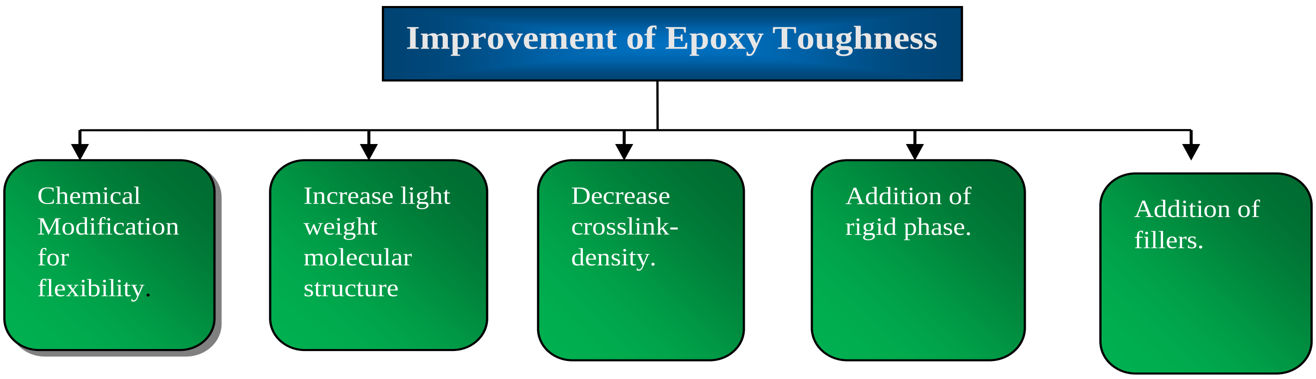


**Figure 7:** Approaches for improvement of epoxy toughness [16].

Toughness is a scientific measure of resistance to Crack growth and a criterion for assessing a material's ability to resist failure and absorb energy [10].

## 15. Fibre reinforced

Reinforcing fibres such as glass and graphite significantly enhance their mechanical performances, enabling epoxies to be used in various structural applications [1]. Over the years, glass-fibre reinforced epoxy materials have been commonly utilised as core elements in boats, automobiles, aircraft, medical and sports equipment's [1]. The performance of fibre reinforcements largely depends on the quality of the polymer matrix after curing [18]. The properties of the continuous reinforcing phase highly influence the mechanical strength of fibre-reinforced polymers (FRPs).

They are also used in fibre reinforced composites for manufacturing the parts, mainly structural parts of wind turbines [22].

Due to their high strength-to-weight ratio, synthetic fibre-reinforced composites are widely used in various technical and engineering applications [12].

## 16. Bio-based

Due to environmental impacts, waste management challenges, and the exhaustion of non-renewable resources, there is increasing attention to producing polymers from renewable resources for industrial applications [13]. In the early 90s, demand for sustainable development in production chains increased significantly. A dynamic cross-linked polymer structure enables both chemical and mechanical recycling of resins and biocomposites [26].

Due to their low cost and eco-friendly characteristics, renewable resources (such as plant oils and starches) have attracted significant research interest [23]. Flame retardants are most promising because they are eco-friendly, highly efficient, and significantly improve the fire safety of epoxy thermosets. Still, their synthesis is somewhat complicated because it involves petroleum-based solvents. This problem was solved by developing eco-friendly materials using sustainable methods [29].

## 17. Advantages

Recently, bio-based research has increased significantly due to its outstanding performance, as they address environmental concerns and enhances the sustainability and biodegradability of materials. Due to these properties of bio-based epoxy materials, they are economically feasible and commercially available [23].

Despite these advantages, bio-based epoxy composites face several challenges. In addition, there are advanced methods for developing these materials, as shown in Table 2.

**Table 2:** Overview of drawbacks and advancements recent advances.

| Recent advances | Drawbacks | Improvement | References |
|---|---|---|---|
| Fracture Toughness | High crosslinking leads to brittle failure. | - Size of rubber particles.- Crosslink density. – Curing agents. | [27] |
| Fibre – reinforced | - Non-biodegradability. –Waste problem. | - Development of natural bio-fibre. -Recycling and reusing processed epoxy resins | [9] |
| Bio-based | -Commercialisation. –Isolation. – Synthesis of flame retardants. | -Processing techniques. -Technology. –Biodegradable and Eco-friendly. | [23, 29] |

## 18. Plant oil-based

Epoxy resins have attracted significant attention for their ecological and economic value. Earlier studies have demonstrated that cross-linking density strongly affects the mechanical and thermal behaviour of plant-oil-based epoxy resin, but this correlation is not yet fully understood. To examine this issue, tung oil-based epoxy systems with different cross-linking densities were fabricated and analysed [30].

Recently, bio-based epoxy materials have gained attention for their inherent biodegradability and reduced reliance on non-renewable resources [30]. Plant oil is a triglyceride whose components depend on the plant type and its growing environment [23]. Plant-based biomaterials are essential because they are renewable and readily available in nature [31]. Cotton, jute, and bamboo are some examples of plant-based biomaterials [31].

## 19. Self-healing epoxies

Self-healing materials are used to repair the affected or damaged area without manual interventions [32].

Microcapsules containing epoxy resin and solvent. These microcapsules are important for the development of self-healing materials, which are cost-effective, low-toxicity, and low-flammability, providing survivability and thermal stability. They must break and open at the right time when the material is damaged, releasing healing agents to repair cracks automatically [33].

## 20. Advantages

These materials are highly valued for their outstanding stability and minimal shrinkage during the curing process [1, 13, 24]. Beyond this, it will also improve mechanical strength, making them an ideal choice for demanding applications [1, 13, 24]. It also shows a high adhesive strength and a high modulus among the materials [1, 13, 22].

Furthermore, the substance exhibits remarkable stiffness or modulus, complemented by its outstanding ability to repel moisture and resist water penetration, ensuring reliability in humid environments [13, 21].

This substance also exhibits remarkable chemical resistance and provides excellent electrical properties [1, 13, 22, 24]. This substance also provides long–term durability and excellent protection against corrosion [1, 13]. Due to these outstanding properties, it is widely used in industrial-grade paints and high-performance coatings [13]. In its liquid state, the resin maintains low viscosity and can be easily modified in systems.

The materials provide high-performance coatings that are widely used in day-to-day life, such as flooring coatings, pipeline coatings, marine coatings, and more [4]. The printed part will achieve a high level of accuracy and rigidity in the materials [14]. The epoxy resin contains a smooth edge and can be applied easily, where it is utilised to facilitate the creation of intricate geometries via 3D printing technologies [14, 21].

## 21. Challenges

Despite these advantages, epoxy resin faces several challenges. These challenges include:

(a) The use of epoxy thermosets in many high-performance applications is limited because of their inherent structural drawbacks[13]Epoxy resins are also challenging with respect to environmental impact and waste management.[1]. In addition, it is poorly soluble in oil and alcohols [21].

(b) Some of the epoxies have low purity, complex structures, crack growth, lack of structural control, brittleness, and reliance on non-renewable resources [4]. It is also toxic when burned [21]. Epoxy materials are flammable and emit harmful gases, posing a risk to personal lives [18].

(c) It shows Low fracture toughness [2, 13] and shows Low impact resistance [13].

(d) It also provides low adhesion if the cracked surface is not properly cleared [21]. It provides crack initiation and a weak growth tendency, which limits its use in structural components and the construction industries [28].

(e) Petroleum resources increase the concerns of environmental issues and human health's [11]. Epoxy resin causes respiratory problems and several allergies.

(f) Epoxy resin is an expensive material because of its outstanding properties and performance. In other words, the epoxy is widely used in paints and coatings to improve the corrosion resistance of materials [9, 14].

## 22. Modification of epoxy resins

The challenges traditionally associated with epoxy resins- this may include inherent brittleness and poor impact resistance, which can be overcome through a strategic chemical modification. By reactive oligomers, low- molecular mass polymers and carbon nanotubes, which will significantly enhance the material's mechanical and thermal performance epoxy matrix [13]. These modifications are achieved by utilising curing agents, resins, and co-monomers with different molecular backbone structures [13]. Thermochemical energy absorption will be enhanced by incorporating various reinforcements into the materials [13]. Modifications to epoxy can enhance properties such as toughness, inherent brittleness, wear resistance, and fire resistance [13]. From an environmental standpoint, the industry is undergoing a shift driven by the depletion of petroleum resources and heightened awareness of the ecological footprint. This will reduce fuel consumption and atmospheric emissions over a long period.

The development of sustainable and eco-friendly biomaterials is used to address the issues associated with petroleum-based materials. In other words, it aims to replace conventional petroleum-based systems [11]. This exacerbates the environmental issues associated with conventional textile production, thereby encouraging the search for eco-friendly biomaterials [11, 12]. However, this conventional epoxy has several issues, whereas the bio-based composites offer various benefits and are more-eco-friendly. The depletion of petroleum reserves will increase environmental awareness [11].

## 23. Future perspectives

The future of epoxy technology lies at the intersection of performance and sustainable development. Hence, researchers primarily focused on addressing these challenges while maintaining their performances.

Green nanocomposite materials and biodegradable epoxy resins are being developed with outstanding properties for structural and nanoscale applications, with the aim of replacing petroleum-based DGEBA materials [13]. In modern industries, especially in the aircraft industry, bio-based resins are still under investigation [34].

One of the primary hurdles is developing a new type of epoxy that is effective for recycling, which is essential for environmental protection and resource conservation. At the time of curing, an irreversible reaction forms a cross-linked structure, making epoxy resins infusible, insoluble, and harder to recycle. The industrial developments lead to the use of more epoxy resin in terms of recycling and waste management.

Researchers are still investigating ways to develop and modify the natural fibre reinforced, flame retarded, biodegradable, renewable and sustainable components [29]. The bio-based epoxies are strongly dependent on future developments, because they enhance their sustainable development and reduce the environmental risks[4]. Epoxy resin manages the environmental waste in socio-economic life [21].

The metallic parts in automobiles and aeroplanes need to be replaced with higher-grade ones because they maintain stability even at high temperatures, up to 300°C [22].

## 24. Conclusions

This paper presents a comprehensive overview of epoxy resins. Epoxy resins are used as essential components in the aerospace, electronics, coatings, structural adhesives, automotive, marine, and construction industries because of their properties. However, except for these applications, they also face several critical challenges- brittleness, limited impact resistance, poor recyclability and environmental concerns associated with bisphenol A (BPA)-based systems, which restrict their long-term sustainability and performance in advanced applications. Significant research has been directed toward overcoming these limitations. Toughening strategies such as rubber modification, thermoplastic blending, and nano-particle reinforcement have improved fracture resistance without compromising stiffness. Furthermore, bio-based epoxy resins derived from renewable resources such as lignin, cardanol, and vegetable oils offer a means to reduce dependence on petroleum-based feedstocks. Future research focuses on sustainable and multifunctional epoxy systems, including self-healing materials, smart conductive composites, high-temperature aerospace matrices, and environmentally benign curing agents. This transition towards BPA-free systems will primarily signal the next generation of epoxy materials. Therefore, rather than complete replacement, the future lies in modifying and redesigning epoxy systems to meet sustainability and performance demands.

In conclusion, epoxy resins will continue to play a dominant role in advanced material systems. However, their long-term relevance depends on the successful integration of green chemistry principles, recyclability and multifunctional performance to address environmental and industrial challenges.

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## Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

## Conflicts of interest

The author declares no conflict of interest.

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## Data availability

No new data were created.

## References

[1] S.H. Goodman, Epoxies, in: *Reference Module in Materials Science and Materials Engineering*, Elsevier (2022).
[2] M. Frigione, M. Lettieri, Recent advances and trends of nanofilled/nanostructured epoxies, *Materials* **13** (2020) 3415.
[3] Chemistry and Technology of Epoxy Resins, Springer, Netherlands (1993).
[4] R. Wang, T. Schuman, Towards green: A review of recent developments in bio-renewable epoxy resins from vegetable oils, *Green Chem.* (2015) 202–241.
[5] K.A. Balaso, S.D. Patil, V. Mahesh, K. Rajesh Kumar, J. Mateti, A scientometric study on the role of resins in high-strength composites: Research trends and industrial applications, *E3S Web Conf.* **648** (2025).
[6] Y. Zhang, X. Liu, M. Wan, Y. Zhu, K. Zhang, Recent development of functional bio-based epoxy resins, *Molecules* **29** (2024) 4428.
[7] Y. Feng, et al., Recent progress in the degradation and recycling of epoxy resin, *J. Mater. Res. Technol.* **32** (2024) 2891–2912.
[8] S. Kumar, S.K. Samal, S. Mohanty, S.K. Nayak, Curing kinetics of bio-based epoxy resin-toughened DGEBA epoxy resin blend: Synthesis and characterization, *J. Therm. Anal. Calorim.* **137** (2019) 1567–1578.
[9] H. Sukanto, W.W. Raharjo, D. Ariawan, J. Triyono, M. Kaavesina, Epoxy resins thermosetting for mechanical engineering, *Open Eng.* **11** (2021) 797–814.
[10] S.R. Mousavi, et al., Toughening of epoxy resin systems using core–shell rubber particles: A literature review, *J. Mater. Sci.* **56** (2021) 18345–18367.
[11] S. Kumar, S.K. Samal, S. Mohanty, S.K. Nayak, Epoxidized soybean oil-based epoxy blend cured with anhydride-based cross-linker: Thermal and mechanical characterization, *Ind. Eng. Chem. Res.* **56** (2017) 687–698.
[12] F.M. Khan, et al., A comprehensive review on epoxy biocomposites based on natural fibers and bio-fillers: Challenges, recent developments and applications, *Adv. Fiber Mater.* **4** (2022) 683–704.
[13] N. Saba, M. Jawaid, O.Y. Alothman, Recent advances in epoxy resin, natural fiber-reinforced epoxy composites and their applications, *J. Reinf. Plast. Compos.* **35** (2015) 447–470.
[14] D. Ying, P. Loke, The epoxy resin system: Function and role of curing agents (2026).
[15] A. Bandyopadhyay, P.K. Valavala, T.C. Clancy, K.E. Wise, G.M. Odegard, Molecular modeling of crosslinked epoxy polymers: The effect of crosslink density on thermomechanical properties, *Polymer* **52** (2011) 2445–2452.
[16] M. Peerzada, S. Abbasi, K.T. Lau, N. Hameed, Additive manufacturing of epoxy resins: Materials, methods, and latest trends, *Ind. Eng. Chem. Res.* **59** (2020) 6375–6390.
[17] S. Hajebi, M. Payamani, H. Fattahi, M. Mortezaei, S. Jalilolghadr, Dual-curing epoxy thermosets: Design, curing, properties and applications, *Polym. Rev.* **65** (2025) 250–280.
[18] N. Rabearison, C. Jochum, J.C. Grandidier, A cure kinetics, diffusion controlled and temperature dependent identification of the Araldite LY556 epoxy, *J. Mater. Sci.* **46** (2011) 787–796.
[19] G. Giannakopoulos, K. Masania, A.C. Taylor, Toughening of epoxy using core-shell particles, *J. Mater. Sci.* **46** (2011) 327–338.
[20] H. Memon, Y. Wei, C. Zhu, Correlating the thermomechanical properties of a novel bio-based epoxy vitrimer with its crosslink density, *Mater. Today Commun.* **29** (2021).
[21] C. Botezatu, B. Oroian, A. Hrituc, I. Condrea, Influences of the circular economy in industrial engineering, *IOP Conf. Ser.: Mater. Sci. Eng.* **591** (2019).
[22] J.C. Capricho, B. Fox, N. Hameed, Multifunctionality in epoxy resins, *Polym. Rev.* **60** (2020) 1–41.
[23] J. Stanzione, J. La Scala, Sustainable polymers and polymer science: Dedicated to the life and work of Richard P. Wool, *J. Appl. Polym. Sci.* **133** (2016).
[24] S.U. Patil, et al., Reactive molecular dynamics simulation of epoxy for the full cross-linking process, *ACS Appl. Polym. Mater.* **3** (2021) 5788–5797.
[25] H. Gu, et al., An overview of multifunctional epoxy nanocomposites, *J. Mater. Chem. C* **4** (2016) 5890–5906.
[26] C. Di Mauro, et al., Chemical and mechanical reprocessed resins and bio-composites based on five epoxidized vegetable oils thermosets reinforced with flax fibers or PLA woven, *Compos. Sci. Technol.* **205** (2021).
[27] H. Kargarzadeh, I. Ahmad, I. Abdullah, Mechanical properties of epoxy–rubber blends, in: *Handbook of Epoxy Blends*, Springer, Cham (2015) pp. 1–36.
[28] M.M.Y. Zaghloul, M.M.Y. Zaghloul, M. Fuseini, Recent progress in epoxy nanocomposites: Corrosion, structural, flame retardancy and applications—A comprehensive review, *Polym. Adv. Technol.* **34** (2023) 3438–3472.
[29] G. Ye, et al., Fabrication of flame-retardant, strong, and tough epoxy resins by solvent-free polymerization with bioderived, reactive flame retardant, *Sustain. Mater. Technol.* **39** (2024).
[30] J. Huang, et al., Influence of crosslinking density on the mechanical and thermal properties of plant oil-based epoxy resin, *RSC Adv.* (2024).
[31] M.T. Rahaman, M.S. Hossain Khan, Biomaterials for manufacturing environmentally sustainable textiles and apparel: Sources, applications, challenges, enablers and future directions, *Int. J. Environ. Sci. Technol.* **22** (2025) 9655–9710.
[32] M.L. Durão, et al., Self-healing composites: A path to redefining material resilience—A comprehensive recent review, *Materials* **17** (2024) 4681.
[33] B.J. Blaiszik, et al., Microcapsules filled with reactive solutions for self-healing materials, *Polymer* **50** (2009) 990–997.
[34] J. Bachmann, C. Hidalgo, S. Bricout, Environmental analysis of innovative sustainable composites with potential use in aviation sector—A life cycle assessment review, *Sci. China Technol. Sci.* **60** (2017) 1301–13.