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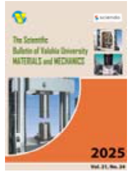

EPOXY-ORGANIC COMPOSITES: A REVIEW ON SUSTAINABLE REINFORCEMENTS, PROCESSING, PROPERTIES, AND APPLICATIONS

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Abstract: *This article offers a thorough review of recent scientific research on the synthesis, characterization, and performance of epoxy-based composite materials reinforced with organic components. It critically evaluates progress made in the past decade in development of composites that incorporate natural fibers, agricultural byproducts, biodegradable polymers, and other bio-derived fillers. By analyzing the existing literature, the review discusses various processing techniques, structural features, and the mechanical, thermal, and chemical properties of these composites. It highlights how organic reinforcements affect the performance of epoxy matrices. The primary objective is to provide an updated overview of current knowledge in epoxy-organic composites, highlighting emerging trends, key challenges, and opportunities for sustainable innovation. The article also compares findings from multiple studies to clarify the relationships between reinforcement types, interfacial interactions, and composite behavior. Furthermore, it underscores the potential of bio-based and hybrid epoxy composites as eco-friendly alternatives to traditional synthetic materials, supporting the global shift toward circular and low-carbon material engineering.*

Keywords: *composites, epoxy resin, eco-friendly materials, reinforcing fibers*

1. INTRODUCTION

The global demand for lightweight, high-performance, and durable materials has grown significantly over recent decades, prompting extensive research into polymer-based composites [1]. Among these, epoxy resins stand out due to their excellent adhesion, high mechanical strength, chemical resistance, and thermal stability, making them suitable for various structural and functional applications [2]. Nonetheless, traditional epoxy composites typically use synthetic fibers such as glass, carbon, or aramid, which are costly and energy-intensive to produce, and present environmental and disposal challenges [3].

As the global shift towards a circular economy and low-carbon technologies accelerates, researchers are increasingly exploring natural and organic reinforcement materials, such as plant fibers, lignocellulosic fillers, and biodegradable polymers, as eco-friendly alternatives to traditional synthetic fibers [4]. These organic reinforcements offer multiple benefits, including being renewable, lightweight, biodegradable, and possessing advantageous specific mechanical properties. Nonetheless, they face notable challenges, including moisture absorption, poor interfacial bonding with hydrophobic epoxy matrices, and variability in quality due to differences in biological origin and processing methods [5].

The addition of natural or biodegradable reinforcements to epoxy matrices enhances the balance between performance and environmental sustainability. Numerous studies have documented the successful creation of epoxy composites reinforced with cellulose fibers, lignin particles, chitosan, natural rubber, and agricultural residues such as rice husk, jute, hemp, or flax [6–9].

This review summarizes the current understanding of epoxy-based composites reinforced with organic materials. It covers the main types of epoxy systems and organic reinforcements, discusses fabrication methods and resulting properties, and highlights key research challenges and opportunities for creating sustainable hybrid materials for advanced engineering uses.

2. EPOXY RESINS – PROPERTIES AND APPLICATIONS

Epoxy resins (ERs) are thermosetting polymers with reactive epoxide groups that can form three-dimensional networks when cured with agents like amines, anhydrides, or phenolic compounds [10]. The most widely used commercial formulation is based on bisphenol-A diglycidyl ether (DGEBA). However, more sustainable and less toxic bio-based alternatives from lignin, cardanol, and vegetable oils have attracted increasing interest recently [11]. During curing, the liquid prepolymer transforms into a rigid, highly cross-linked structure, offering excellent adhesion, dimensional stability, and mechanical strength [2].

Epoxy resins are widely used in automotive, marine, electronics, and civil engineering due to their excellent chemical resistance, mechanical strength, and minimal decrease during curing. They function as matrices in advanced fiber reinforced composites, high-performance coatings, electrical encapsulants, and structural adhesives. These resins offer high tensile and flexural strength, strong bonding with different reinforcements, and excellent resistance to moisture and corrosive conditions. Although conventional petroleum-based epoxies provide these benefits, they also have notable drawbacks, including brittleness, limited impact toughness, and a lack of recyclability after cross-linking [14]. Additionally, their production relies heavily on non-renewable resources, prompting research into bio-based epoxy systems and the addition of natural fillers or fibers to improve sustainability and performance [15].

In a composite structure, the epoxy matrix acts as the continuous phase, facilitating stress transfer, protecting the reinforcement from environmental factors, and defining the material's overall thermal and chemical stability. When used with organic reinforcements like lignocellulosic fibers or agricultural residues, hybrid composites can achieve lower density, enhanced energy absorption, and a degree of biodegradability.

Recent progress in renewable epoxy systems and hybrid organic epoxy composites demonstrates a move toward eco-friendly, circular economy-focused material design. These developments demonstrate that epoxy-based composites can provide both mechanical strength and environmental sustainability, making them strong options for sustainable engineering applications [16].

3. ORGANIC REINFORCEMENT MATERIALS

Organic reinforcement materials from renewable and biodegradable sources are obtaining popularity as eco-friendly alternatives to synthetic fibers and mineral fillers in epoxy composites [1]. These include natural fibers from plants, agricultural by products, lignocellulosic particles, and biodegradable polymers. Using organic reinforcements reduces the overall material weight and production costs, while also contributing to the development of sustainable composites with enhanced mechanical and environmental properties. Their application supports circular economy principles by transforming low value biomass or waste into high-performance engineering materials [17].

3.1. Natural fibers

Plant-based fibers like flax, jute, hemp, sisal, kenaf, and bamboo are among the most studied reinforcement materials for epoxy matrices. These fibers mainly consist of cellulose, hemicellulose, lignin, and pectin, which contribute to their natural strength and rigidity [16]. Their benefits include low density, high specific strength, renewability, and biodegradability [18]. Nevertheless, their hydrophilic nature and weak interfacial bonding with hydrophobic epoxy can cause ineffective stress transfer and mechanical deterioration in humid environments [19]. To improve adhesion and compatibility, various surface treatments, including alkalization (NaOH), silane coupling, acetylation, and enzymatic modification, have been employed, resulting in notable enhancements in tensile, flexural, and impact properties [20].

Research indicates that chemically treated natural fiber epoxy composites can match or surpass the mechanical properties of glass fiber reinforced composites even at lower weight fractions [21]. Additionally, hybrid configurations with two or more natural fiber types (such as flax jute or kenaf hemp) have shown enhancements in toughness and dimensional stability [22]. Selecting the appropriate fiber type, volume fraction, and treatment method is crucial for optimizing both mechanical performance and moisture resistance.

3.2. Agricultural and Organic Waste Reinforcements

Agricultural residues, such as rice husk, coconut shell powder, banana stem fibers, walnut shells, and wood flour, are significant organic fillers in epoxy composites [23]. These waste-based materials are cost-effective and readily available, providing a sustainable approach to valorising waste. For example, rice-husk-filled epoxy composites show increased rigidity and wear resistance, while coconut shell powder and wood flour improve hardness and dimensional stability [24]. The particle size and surface chemistry of these fillers have significant impact on the interfacial adhesion and mechanical properties of the composites [25]. Additionally, lignin, cellulose nanocrystals (CNCs), and starch-based particles have been incorporated into epoxy systems to create biodegradable composites with higher modulus and lower environmental impact [26].

3.3. Biopolymers and Hybrid Organic Reinforcements

Recently, biodegradable polymers like polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polycaprolactone (PCL) have been explored as co-reinforcements or blending agents in epoxy matrices. These biopolymers can improve the ductility and fracture toughness of normally brittle epoxy systems [27]. Additionally, creating hybrid composites that combine natural fibers and biopolymers in an epoxy matrix has been shown to generate synergistic effects, leading to materials that effectively balance mechanical strength, flexibility, and biodegradability [28].

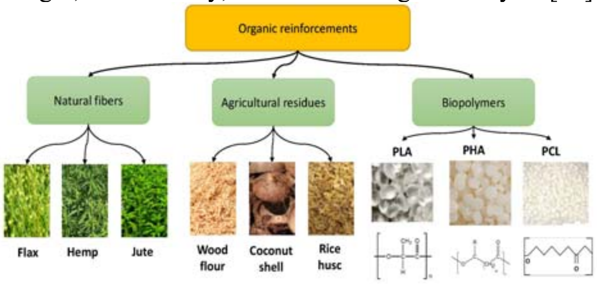

Figure 1 – Most frequently used organic reinforcement materials

Integrating organic reinforcements into epoxy matrices provides a promising mode for developing high-performance, sustainable composites. Nonetheless, challenges like long-term durability, moisture sensitivity, and manufacturing scalability still need to be addressed. Future studies should focus on enhancing interfacial engineering and developing fully bio-based epoxy systems that can achieve the strength, toughness, and cost efficiency of traditional petrochemical composites.

4. FABRICATION METHODS OF EPOXY–ORGANIC COMPOSITES

Creating epoxy composites with organic reinforcements demands precise control over processing parameters to achieve uniform dispersion and strong interfacial bonding between matrix and reinforcement. The choice of manufacturing process primarily depends on the reinforcement's physical form (fibers, particles, or powders), resin viscosity, and the final application's requirements. Commonly used techniques include hand lay-up, compression moulding, vacuum bagging, resin transfer moulding (RTM), and stir casting, with newer methods like additive manufacturing and microwave curing gaining popularity [17]. Table 1 presents the principal fabrication methods used in the development of epoxy–organic composite materials

Table 1. Comparative analysis of principal fabrication methods of epoxy–organic composite materials with their advantages and disadvantages

METHOD	PROCESS DESCRIPTION	ADVANTAGES	LIMITATIONS
1. Hand Lay-up and Casting	Manual impregnation of fiber layers with epoxy; casting involves mechanically mixing particulates into resin.	Low cost, simple, suitable for various reinforcements.	Possible air entrapment; vacuum assistance improves quality.
2. Compression Moulding and Hot Pressing	Resin–reinforcement mix placed in heated mold under pressure; hot pressing improves flow and curing speed.	Improved mechanical strength, reduced porosity, better bonding.	Requires precise control of parameters; specialized equipment.
3. Vacuum Bagging and RTM	Vacuum removes trapped air and excess resin; RTM injects resin into closed mold with preform.	High-quality composites, uniform impregnation, low voids.	Higher equipment cost and process control needs.
4. Surface Treatment and Interface Engineering	Chemical, physical, and advanced interfacial methods improve fiber–matrix adhesion.	Better wettability, adhesion, stress transfer, moisture resistance.	Some treatments may leave residues; optimization required.
5. Emerging and Hybrid Techniques	Microwave curing, solvent-free methods, additive manufacturing, hybrid thermal–vacuum processes.	Faster curing, energy efficient, improved properties, sustainable.	Developing technologies requiring advanced equipment.

4.1. Hand Lay-up and Casting

The hand lay-up process is one of the simplest and most cost-effective methods for fabricating epoxy composites reinforced with either synthetic or natural fibers. In this process, layers of organic reinforcement (woven, chopped, or randomly oriented) are manually impregnated with liquid epoxy resin and then cured, either at room temperature or under elevated heat conditions. The casting technique, often used for particulate or powdered reinforcements, involves mechanically mixing the filler into the resin matrix to ensure even dispersion before the resin cures [29]. Although straightforward, the hand lay-up method can cause issues such as air entrapment and uneven fiber distribution; however, vacuum-assisted impregnation can significantly improve composite uniformity and enhance mechanical performance [30].

4.2. Compression Moulding and Hot Pressing

Compression molding is commonly used to produce epoxy composites reinforced with natural fibers or particles from agricultural waste. The pre-mixed resin–reinforcement mixture is placed into a heated mold under controlled pressure, ensuring proper wetting and reducing void formation. Processing parameters such as curing temperature, applied pressure, and holding time are essential for achieving even cross-linking and high dimensional accuracy [31]. By optimizing compression moulding conditions enhances tensile and flexural strength, reduces porosity, and improves interfacial adhesion between the epoxy matrix and lignocellulosic reinforcements. Hot pressing, a variant of this method, encourages better resin flow and faster curing, making it especially suitable for hybrid composites that incorporate multiple reinforcement types [32].

4.3. Vacuum Bagging and Resin Transfer Moulding (RTM)

Vacuum bagging and resin transfer molding (RTM) are preferred methods for producing high-quality structural composites with uniform fiber impregnation. In vacuum bagging, a vacuum is applied to a laminated preform to remove trapped air and excess resin. The result is a compact composite with enhanced mechanical properties [33]. RTM involves injecting epoxy resin into a closed mold containing the preform under controlled pressure, enabling precise regulation of resin flow and fiber volume fraction. Although these techniques involve higher equipment costs and require strict process control, they yield composites with excellent reproducibility and minimal voids, critical features for aerospace and automotive applications [34].

4.4. Surface Treatment and Interface Engineering

Achieving strong interfacial adhesion between hydrophobic epoxy resins and hydrophilic organic reinforcements is a key challenge in composite fabrication. To enhance wettability and bonding, natural fibers are often surface - modified with chemical treatments such as alkalization, silanization, or permanganate oxidation [19]. Additionally, physical methods such as plasma exposure, corona discharge, and enzymatic processing can increase surface roughness and enhance fiber - matrix compatibility without leaving chemical residues [35]. Researchers are also exploring advanced interfacial engineering techniques, including coupling agents, compatibilizers, and nanostructured interlayers, to boost stress transfer efficiency and moisture resistance in bio-based epoxy composites [36].

4.5. Emerging and Hybrid Fabrication Techniques

Recent research has explored new fabrication techniques for epoxy composites, including microwave-assisted curing, solvent-free methods, and additive manufacturing. Microwave curing significantly reduces processing times and lowers energy consumption, while ensuring more uniform cross-linking [37]. Moreover, hybrid methods that combine compression molding with vacuum- or heat-assisted curing have been shown to boost the mechanical and thermal properties of composites reinforced with natural or biodegradable materials [38]. These advancements contribute to the development of manufacturing processes that are more energy-efficient, scalable, and environmentally friendly, paving the way for next-generation epoxy–organic composites.

5. MECHANICAL AND THERMAL PROPERTIES OF EPOXY–ORGANIC COMPOSITES

The mechanical, thermal, and chemical properties of epoxy organic composites are influenced by the type, volume fraction, surface treatment, and dispersion of the reinforcement, as well as the curing conditions of the epoxy matrix. Adding natural fibers, lignocellulosic fillers, or biodegradable polymers typically enhances stiffness and specific strength, while also lowering density and environmental footprint compared to plain epoxy. Achieving an optimal balance between interfacial bonding and load transfer is crucial for the overall performance of composites [20].

5.1. Mechanical Properties

Mechanical reinforcement is a primary reason for incorporating organic materials into epoxy matrices. Multiple studies consistently demonstrate significant improvements in tensile and flexural strength when natural fibers or particulate fillers are chemically treated and added at optimal levels, typically between 10% and 30% by weight [39]. For instance, epoxy composites reinforced with kenaf and jute fibers have achieved up to a 60% increase in tensile strength and a 40% higher flexural modulus compared to unreinforced epoxy [9]. Additionally, fillers such as rice husk and coconut shell powder enhance hardness and wear resistance by effectively distributing stress and deflecting cracks [23].

However, excessive filler loading or poor dispersion can cause agglomeration, void formation, and reduced ductility [40]. Hybrid composites that blend natural and synthetic fibers (such as flax-glass, jute-carbon) demonstrate synergistic enhancements in toughness and energy absorption, offering a balanced compromise between mechanical strength and biodegradability [41].

Fatigue and dynamic mechanical analysis (DMA) reveal that bio-reinforced epoxy composites maintain strong stiffness and damping over a broad temperature range. Typically, the storage modulus increases with higher reinforcement levels, while the glass transition temperature (Tg) shows minor variations influenced by interfacial adhesion and cross-linking density [42].

5.2. Thermal Properties

Thermal analyses using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) reveal that organic reinforcements can influence the curing behavior and thermal stability of epoxy systems. Natural fibers and lignin-based fillers act as both reinforcing and insulating agents, restricting polymer chain mobility and raising the initial degradation temperature by 10–25 °C relative to pure epoxy [43].

Hybrid bio-fillers that incorporate lignin or silica-rich agricultural residues, such as rice husk, have demonstrated enhanced flame retardancy and lower mass loss rates due to the formation of protective char layers during pyrolysis. The thermal conductivity of these composites can be tailored by selecting different filler types. Cellulose nanocrystals and graphene-coated fibers enhance thermal conductivity, whereas starch- or wood-flour-based fillers reduce it, making the composites ideal for thermal insulation applications.

6. APPLICATIONS AND FUTURE PERSPECTIVES

Epoxy–organic composites have become versatile materials that fulfill both structural and environmental requirements across many industries. Their benefits, including a high strength to weight ratio, corrosion resistance, and biodegradability potential, enable their use in applications that were once dominated by synthetic fiber reinforced composites. Sectors like construction, automotive, aerospace, marine, and consumer goods are increasingly embracing bio-based epoxy systems and natural fiber reinforced composites as sustainable alternatives [41].

6.1. Industrial and structural applications

In the construction industry, epoxy composites reinforced with lignocellulosic fibers and agricultural waste are increasingly used in non-structural and semi-structural elements such as wall panels, ceiling boards, door frames, and flooring tiles. Their excellent dimensional stability, lightweight design, and moisture resistance make them ideal for architectural cladding and decorative purposes. Additionally, epoxy composites strengthened with rice husk and wood flour show significant potential for thermal insulation and acoustic damping in eco-friendly building systems [40].

In the automotive and transportation sectors, natural fiber–reinforced epoxy composites are increasingly used for dashboards, interior panels, seatbacks, and trunk liners as alternatives to traditional glass fiber-reinforced composites [39]. Replacing heavier materials with these composites leads to improved fuel efficiency and reduced CO_2 emissions [5]. Hybrid composites that combine natural fibers with synthetic ones (such as flax, glass, or jute carbon) offer mechanical properties comparable to those of conventional materials. However, they have a substantially lower environmental impact.

6.2. Research Trends and Future Prospects

Future research will likely focus on developing entirely bio-based epoxy systems from renewable materials, such as lignin, cardanol, and epoxidized vegetable oils. These are to be combined with optimized natural reinforcements to match or outperform traditional composite properties in terms of mechanical strength and thermal stability [11]. Incorporating nano-reinforcements such as cellulose nanocrystals, graphene oxide, or nanoclays into epoxy matrices has also shown promising results, enhancing barrier performance, electrical conductivity, and thermal stability while promoting environmental sustainability [44].

In conclusion, the continued advancement of epoxy–organic composites represent a significant step toward sustainable materials engineering. By integrating renewable resources, energy-efficient manufacturing techniques, and recyclable solutions, these materials can significantly reduce the environmental footprint of future industry practices.

7. CONCLUSIONS

Epoxy organic composites are a quickly developing class of materials that balance high-performance engineering needs with sustainability goals. Incorporating natural fibers, agricultural residues, lignocellulosic particles, and biodegradable polymers into epoxy matrices has been successful in lowering environmental impact while preserving or improving mechanical and thermal performance.

Using bio-based reinforcements reduces both density and cost, promoting circular economy principles by using renewable or waste-derived resources. Recent studies on fully bio-based epoxy resins, hybrid organic–synthetic systems, and nanostructured fillers indicate that sustainable composites can match the performance of traditional glass or carbon fiber materials.

Nevertheless, challenges persist regarding moisture sensitivity, long-term stability, and industrial scalability. Future efforts should focus on developing durable interfacial chemistries, improving life-cycle assessment methods, and advancing eco-friendly processing technologies to achieve full recyclability and cost competitiveness. Overall, epoxy-organic composites offer a promising route for developing the next generation of lightweight, sustainable, and multifunctional materials that align with global initiatives for low-carbon and circular materials engineering.

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