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Review of glass fiber reinforced of epoxy based composite materials

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ABSTRACT

Recently, glass fiber-reinforced epoxy composite materials have shown great promise for a variety of applications. This review offers an in-depth overview of these composites, focusing on their core components, manufacturing processes, and performance characteristics such as mechanical strength and thermal stability. It discusses various types of glass fibers and epoxy resin formulations, alongside advanced fabrication methods like vacuum infusion, and Resin Transfer Molding which significantly influence their structural robustness and application flexibility. The review examines critical mechanical properties including tensile, flexural, impact, and fatigue behaviors as well as thermal and chemical durability essential for challenging operational environments. Additionally, the study highlights the mechanical and thermal responses of different glass fiber reinforced polymer composites under load, emphasizing their significance in modern industry sectors. Insights into their multiple applications, from automotive and construction to marine and recreational products are provided, illustrating their growing importance in engineering advancements. The conclusion underscores ongoing challenges and future opportunities in optimizing epoxy-glass fiber composites to meet emerging technological demands.

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1. Introduction

Polymer-based composite materials have gained considerable prominence across various fields, driven by rapid technological progress. It has become increasingly feasible to develop high-performance polymer matrix composites economically by reinforcing low-cost polymers with suitable fillers tailored to specific needs [1]. Typically, composite materials consist of one or more discontinuous phases embedded within a continuous phase. When multiple discontinuous phases of differing types are present, the composite is classified as hybrid. The continuous phase is termed the matrix, while the discontinuous phases are known as reinforcements or reinforcing agents. These materials combine components with complementary physical and mechanical characteristics [2, 3]. Fig. 1 shows the classification of different composites. Glass fiber-reinforced composites are especially attractive because their properties can be customized for a broad spectrum of applications [4, 5]. With glass fibers constituting about 70–75% by weight (or 50–60% by volume), selecting the appropriate type of glass is crucial [6]. Glass-fiber composites are a subset of fiber-reinforced polymer composites. They are valued for their low density, high strength, and ease of processing, making them popular in sectors such as aerospace, automotive, and construction [7, 8]. Historically, glass fibers have been used since ancient times Egyptians crafted containers from heat-softened glass fibers, and continuous glass fibers emerged in the 1930s primarily for electrical applications. Today, these fibers find applications in electronics [9-11], aviation [12-15], civil construction [16-18], automotive industries [19-25], marine [26-31] and sports [32-34] owing to their exceptional properties like high strength, flexibility, stiffness, and chemical resistance. They are manufactured in various forms such as rovings, chopped strands, yarns, fabrics, and mats, each with unique characteristics suited to specific composites. Studies have reported on the thermal, tribological, water absorption, mechanical, and vibrational properties of these reinforced materials [8, 35, 36].

The mechanical performance of fiber-reinforced composites fundamentally depends on the properties of their constituent's fiber type, amount, orientation, and distribution as well as the nature of the fiber-matrix interface, which governs load transfer mechanisms. Additionally, the inclusion of fillers and additives has become a common practice to enhance or modify composite properties, playing a vital role in their mechanical and physical performance for industrial applications [37].

The novelty of this review lies in its comprehensive and integrated examination of glass fiber-reinforced epoxy composites, highlighting recent advances in fabrication techniques such as vacuum infusion and Resin Transfer Molding and their impact on material performance.

It uniquely combines a detailed analysis of mechanical, thermal, and chemical properties with an exploration of diverse applications across multiple industries, offering valuable insights into the relationship between manufacturing processes and functional performance. Additionally, the review emphasizes emerging challenges and future opportunities, providing a holistic perspective that bridges fundamental material science with practical engineering solutions, an approach that enhances understanding and guides future research and development in epoxy-glass fiber composites.

2. Types of glass fiber

Glass fibers are produced from molten raw materials like silica from sand, alumina from clay, calcium oxide from calcite, and boron oxide from colemanite resulting in various compositions exhibiting properties such as alkali resistance or enhanced mechanical strength [38].

They are classified according to their intended application and include forms such as chopped strands, rovings, woven fabrics, and mats, used in processes like injection molding, filament winding, pultrusion, sheet molding, and hand layup [39].

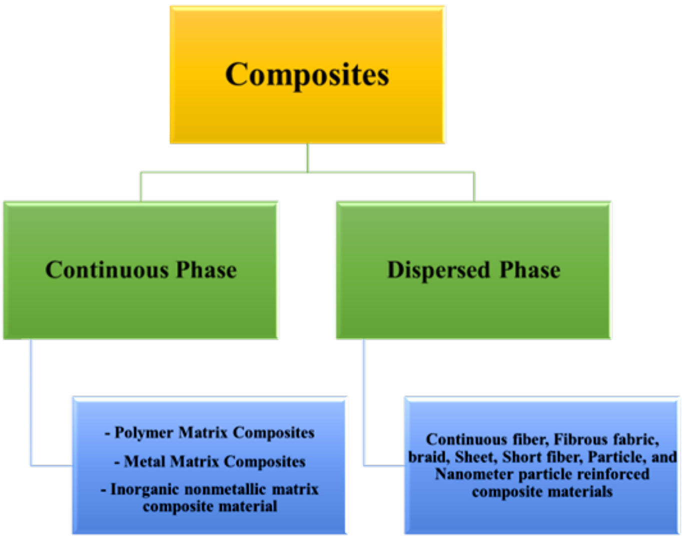

Fig. 1. Classification of composites.

They are classified according to their intended application and include forms such as chopped strands, rovings, woven fabrics, and mats, used in processes like injection molding, filament winding, pultrusion, sheet molding, and hand layup [39]. In a research, Morampudi et al. [40] reviewed the properties of different Glass fiber-reinforced polymer (GFRP) composites prepared via various fabrication techniques, concluding that high-quality composites typically utilize S-Type glass combined with epoxy or polyester matrices, mainly for aerospace purposes. These are costly but offer superior performance. Conversely, for general household and furniture applications, E-Type glass less strong but more economical is preferred for mass production. Key temperature-related properties such as glass transition temperature, fiber orientation, and fiber volume fraction influence their operational limits. Different types of glass fibers are available, including E-glass, C-glass, S-glass, A-glass, D-glass, R-glass, EGR-glass, and Basalt fibers [35]. For instance: A-Glass (Alkali-rich, used as inexpensive filler despite poor chemical resistance.), C-Glass (Chemically resistant but lower strength.), D-Glas (Superior electrical properties but low strength.), S-Glass (High strength and stiffness, but manufacturing complexity raises costs.), AR-Glass (Impact-resistant with zirconium, but high melting points limit uses.), E-Glass (The most common (comprising 50% of the market) due to affordability, electrical insulating ability, and water resistance, but environmental concerns related to boron oxide and fluorine content exist) [41, 42].

Glass fibers are available in various forms, such as continuous threads, woven fabrics, random mats, and chopped strands, each suited for specific composite manufacturing processes [43].

3. Epoxy resin systems

3.1.1. Types of epoxy resins

Epoxy resin is a thermosetting polymer with at least one reactive epoxy group, prized for its high reactivity with functional groups like carboxyl, amino, and hydroxyl groups [44, 45]. Its versatility stems from these reactive sites, making it suitable for applications including printed circuit boards, structural adhesives, electronics sealants, and more. About 90% of the world's epoxy resins are based on diglycidyl ether of bisphenol A (DGEBA), produced by reacting bisphenol A with epichlorohydrin [46].

Various epoxy resins are available, including water-soluble polyether or sorbitol-based types, eugenol epoxy, sulfur-based variants, derivatives of bisphenol A [47], and hydrogenated terpinene–maleic ester type epoxy resin [48]. The properties of epoxy systems are tailored through their chemical structures to meet specific application demands. These can be categorized as:

Liquid epoxy resins like DGEBA are widely used due to their excellent adhesion and mechanical properties. Solid DGEBA-based resins, derived from DGEBA, are recognized for their strong performance and adhesion. Phenoxy resins are high-molecular-weight derivatives noted for their chemical resistance and excellent insulating capabilities. Epoxy thermoplastics merge epoxy chemistry with thermoplastic features, enhancing toughness and processing ease. Halogenated epoxy resins, which contain halogen atoms such as bromine or fluorine, are engineered to improve flame retardancy and chemical resistance. Multifunctional epoxy resins, with multiple reactive sites, increase cross-link density, thereby boosting thermal and mechanical performance. Epoxy novolacs, based on phenol formaldehyde resins including Bisphenol F, cresols, and various glycidyl ethers, offer customizable properties. Other polynuclear phenol glycidyl ethers, like tetrakis(4-hydroxyphenyl)ethane derivatives, are designed for specific applications. Lastly, aromatic glycidyl amine resins are distinguished by their high thermal stability and mechanical strength [49].

3.2. Properties of epoxy resins

Curing agents are vital for formulations of aqueous epoxy resin systems. However, their application is somewhat limited due to low emulsification efficiencies [50]. Epoxy resins find extensive use in electronic components [45, 51, 52], casting [53, 54], packaging [52, 55, 56], adhesives, corrosion protection, and dip coating processes. When combined with curing agents, epoxy resins transform into rigid, infusible materials. The evolution of vulcanization-related properties now emphasizes eco-friendliness and enhanced mechanical performance. Curing agents are utilized for surface modifications, optimizing thermodynamic properties, functional treatments in therapeutic approaches, and have driven recent innovations across various sectors, including commercial and industrial applications [50].

4. Fabrication techniques

4.1. Vacuum infusion

Vacuum infusion is a manufacturing process where vacuum pressure pulls resin into dry fiber reinforcements within a mold, resulting in high-quality composites with good fiber-resin ratios [57, 58]. This method is also known as the resin film infusion . It typically uses low-viscosity resins and sometimes flow media to facilitate resin flow [57, 58]. While it offers benefits like reduced emissions, better product consistency, and lower resin use, challenges include slow cycle times, higher consumable costs, and difficulty ensuring uniform vacuum pressure for large structures [57]. Advances include the development of thermoplastic resins, such as PA-12 and Elium® [59] which enable room-temperature processing, though the process still faces limitations like resin gelation and vacuum control issues [58].

4.2. Matched die molding

Matching die molding methods create components that are highly consistent and close to their final shape with little effort, often displaying two or more polished surfaces. These methods encompass processes such as injection molding, silicone rubber molding, compression molding, low-pressure molding, transfer molding, resin transfer molding, and reaction injection molding [43, 60, 61].

4.2.1. Injection molding

Injection molding (IM), often called "thermoplastic injection," involves injecting heated or molten thermoplastic into a closed mold under high pressure. It is a reversible process comprising parts such as the nozzle, moving and stationary plates, heating elements, feed hopper, and various mechanical systems. The molds are typically made from aluminum alloys for cost efficiency, allowing quicker processing. The process involves feeding granulated or powdered composite material into the machine, where it's heated (up to 200 °C), softened, and then injected into the mold cavity via a hydraulic system. After cooling, the solidified part is ejected [43].

4.2.2. Resin transfer molding (RTM)

RTM, also termed liquid molding, is a process suited for producing high-performance composite parts in moderate volume.

It involves injecting low-viscosity thermoset resin into a sealed mold containing prearranged reinforcement fabrics, often under low pressure (3.5–7 bar). RTM caters to various fiber forms woven fabrics, mats, and tows—and enhances strength and stiffness when using glass or carbon fibers in the reinforcement [43, 62-64].

In a study, Kim et al. [65] studied the production of glass fiber-reinforced PLLA composites via in-situ polymerization using RTM. The low viscosity of lactide enhanced its penetration into fibers, achieving a 100% conversion for GFRP and 91.9% for PLLA.

The addition of glass fibers increased the crystallinity to 55.65%, compared to 36.5% for pure PLLA. The resulting composite exhibited excellent mechanical properties, with a tensile strength of 122.3 MPa and a modulus of 4.485 GPa. During degradation, both surface and bulk erosion occurred, suggesting these composites could serve as alternatives to metallic implants in medical applications. Fig. 2 shows the schematic diagram of High-pressure RTM process.

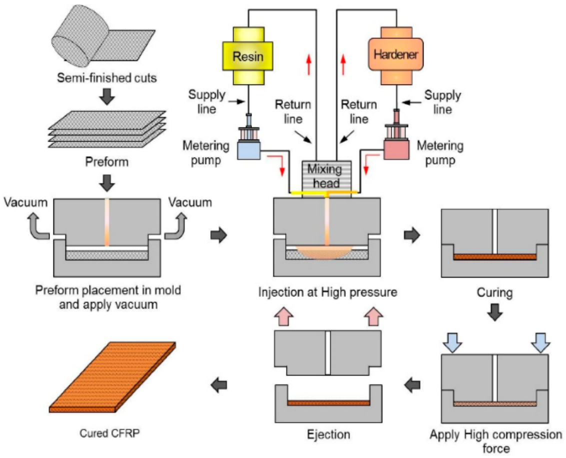

Fig. 2. Schematic diagram of high-pressure resin transfer molding process [66].

4.2.3. Vacuum-assisted resin transfer molding

Vacuum-assisted resin transfer molding (VARTM) was developed over the past two decades. It is a variant of RTM employing a vacuum to improve resin flow. Also known as VARI, VBRTM, or VIM, it replaces part of the mold with a flexible vacuum bag. The process involves preplacing reinforcing fabrics held together by binders in a mold, sealing with a [67] vacuum bag, and injecting resin under vacuum pressure. Post-impregnation, the composite cures at room temperature, with optional post-curing [68].

Fig. 3 demonstrates schematic of the enhanced device-based VARTM process. In a research, Aranha et al. [68] investigated water sorption in hybrid polyester composites reinforced with glass and jute fabrics, produced via compression and VARTM. The study tested five stacking sequences at room temperature, 50°C, and 70°C. Water absorption and diffusion coefficients were intermediate compared to single-fiber composites, with no significant differences once saturated. Higher diffusion rates were observed in specimens with jute on outer surfaces, especially at elevated temperatures. The manufacturing method did not influence saturation water absorption. Overall, jute content and immersion temperature mainly affected moisture uptake, while the fabrication process had little effect on saturation water sorption. Other methods in this category include silicone rubber and compression molding processes [43].

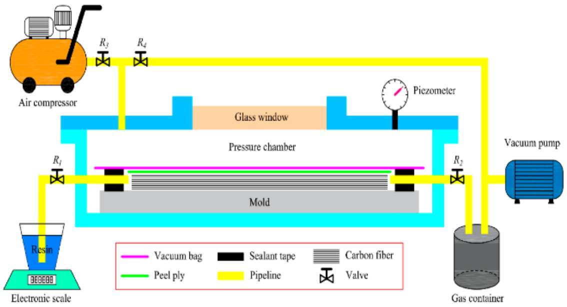

Fig. 3. Enhanced device-based vacuum-assisted resin transfer molding process [69].

4.3. Contact molding

Contact molding methods are cost-effective for producing single finished surfaces and shorten development times due to simplified tooling [43].

4.3.1. Dry hand lay-up

This basic and longstanding technique involves manually placing layers of reinforcement within a mold and applying resin. It's widely used for large, low-volume parts such as boat hulls, car body panels, wind turbine blades, and household products like pools and tubs [43].

4.3.2. Spray lay-up

Spray lay-up is similar in simplicity to hand lay-up but is faster and can produce more complex shapes. It uses open molds and usually cures at room temperature, with heating possible to accelerate curing. Ideal for larger parts like bathroom units and ventilation hoods in small to medium production runs [43].

4.3.3. Filament winding

This automated process is suitable for manufacturing cylindrical and pressure vessel structures by winding prepreg fibers (glass, carbon, Kevlar) around rotating cores using helical, circumferential, or polar patterns [70].

4.3.4. Pultrusion

Pultrusion is a continuous process in which fibers are pulled through a resin bath and then into a heated die, creating high-strength, stiff components with a consistent cross-section [71, 72]. In one study, Irfan et al. [73] introduced a modified pultrusion process replacing the traditional resin bath with a custom resin impregnator, coupled with fiber spreading for better impregnation. They used DSC to optimize die temperature and process speeds. A dimensionless impregnation number was developed to evaluate impregnation efficiency considering various impregnation modes. Experiments at different speeds showed that the modified method slightly improved mechanical properties and significantly reduced solvent use and resin waste, offering notable environmental advantages over conventional pultrusion.

4.3.5. Autoclave molding

Autoclave Molding is an advanced process that uses high pressure (around 5 bar) in a sealed autoclave, producing dense, high-quality composites with variable fiber orientations. It is predominantly used in aerospace due to its cost and performance benefits [43, 74, 75].

5. Mechanical properties

5.1. Tensile strength and modulus

Embedding fibers in a matrix creates composites that bind, transfer loads, and protect fibers. Key factors affecting performance include fiber orientation, fiber strength, physical properties, and interfacial adhesion. Fiber strength determines load-bearing capacity, while modulus influences stiffness and rigidity, both crucial for composite effectiveness [76].

In a research by Devendra and Rangaswamy [37], the mechanical behaviors of epoxy composites reinforced with E-glass fibers was studied, filled with various additives like fly ash, aluminum oxide, magnesium hydroxide, and hematite. They found that composites with 10% magnesium hydroxide displayed the highest tensile strength (~375.36 MPa), while those with fly ash had the greatest impact strength. Additionally, increasing alumina and hematite contributed to higher hardness levels, though excessive addition reduced strength and impact resistance. Additionally, Asi et al. [77] studied the effect of Al_2O_3 particles on glass-fiber reinforced epoxy composites. Up to 10% Al_2O_3 improved flexural strength (by 33%) and flexural modulus (by 78%), but higher contents reduced tensile and shear strengths.

5.2. Flexural strength and modulus

Flexural strength and modulus assess a composite's ability to resist bending forces and its stiffness under flexural loading [78]. In a study by Sundeep et al. [79], the use of natural fiber-reinforced hybrids like E-glass and pineapple leaf fiber for cost-effective, lightweight, high-strength materials was highlighted. Their mechanical tests focused on tensile and flexural properties of specimens made via Hand Lay-Up, aiming to optimize composite performance.

In another study, Kumar et al. [1] developed epoxy-based hybrid composites using a manual layup process with clamp load, reinforcing epoxy with glass fiber (via stranded mats) and nanocarbon particles at various weight percentages. Their study examined impact and flexural strengths, employing response surface methodology for analysis. Results indicated that the reinforcement content significantly influenced both flexural and impact behaviors, with composites containing both glass fibers and carbon nanoparticles exhibiting superior performance in these areas. Additionally, Singh et al. [80]. explored the influence of fiber content on the mechanical behavior of glass fiber-reinforced epoxy composites. Their results showed that both tensile and flexural strengths significantly depend on the fiber volume fraction within the matrix. Reinforced composites consistently outperformed unreinforced epoxy, with a 20% increase in glass fiber content leading to a 14.5% rise in tensile strength and a 123.65% increase in flexural strength. The greater enhancement in flexural strength is attributed to the fibers' contribution to overall stiffness. Additionally, the Young's modulus increased with higher fiber content, indicating improved strength and reduced deformation.

5.3. Impact resistance

Impact resistance measures how well a composite can absorb energy and withstand sudden forces without failure . In a study by Zaretsky et al. [81] the impact behavior of woven glass-epoxy composites under high-velocity impacts was investigated. Results showed microstructural effects led to longer acceleration durations and altered wave speeds, with damage accumulating only after certain pressure thresholds [81].

5.4. Fatigue behavior

Fatigue behavior describes how composites respond to repeated loading, which can cause progressive damage over time [82-84]. In a study, the tensile fatigue life of glass fiber/epoxy composites embedded with shape memory alloy wires was studied by Wang and colleague [85].

The composites were fabricated through vacuum-assisted resin infusion. The tests involved cyclic tensile loading, with fracture surfaces and failure modes analyzed across different stress levels. Results revealed that the SMA-reinforced composites exhibited more than double the fatigue life compared to plain GF/epoxy composites. SEM analysis of fractured surfaces provided insights into the failure mechanisms. The fatigue life was characterized by S-N curves, and residual strength and stiffness were recorded post-testing. The findings demonstrated significant improvements due to SMA incorporation. In another study, Selmy et al. [86] performed flexural fatigue tests on glass fiber/epoxy laminates, finding that with cyclic loading, a 20% loss in flexural stiffness. Statistical analysis modeled their fatigue life using Weibull distributions.

5.5. Velocity impact

Velocity impact examines the effects on composites when subjected to high-speed impacts, important for crash and ballistic applications [87].

In a research, Safri et al. [88] investigated impact damage in GFRP plates made of C-glass/epoxy and E-glass/epoxy using high-velocity gas gun and drop weight tests. They studied the effects of specimen thickness, projectile type, impact velocity, number of plies, and impact energy on failure modes through nondestructive testing. High-velocity tests showed fiber and matrix cracking, with the E-glass/Epoxy experiencing less damage, indicating greater strength due to higher fiber volume and density. The findings suggest that E-glass/epoxy (800 g/m²) is better suited for aircraft structures.

6. Thermal and chemical resistance

6.1. Thermal properties- conductivity

The thermal conductivity of a composite determines how efficiently it transports heat across its structure [89]. In a study by Patnaik et al. [90], composite samples with varying amounts of randomly oriented E-glass fibers (4 different weight percentages) embedded in epoxy were prepared to analyze physical, mechanical, and thermal behavior. Simulations using ANSYS software, based on a finite element model and the representative area element approach, validated experimental results, showing close agreement in elastic moduli and tensile strength. An empirical formula was developed to estimate the effective thermal conductivity of fiber-matrix systems. The thermal conductivity increased with higher glass fiber content, peaking at 45 wt.%, then slightly decreasing at lower weights, aiding in economical design of composites for specific structural needs in early-stage R&D. In another study, Braga and Magalhaes [91] also examined the mechanical and thermal behaviors of epoxy composites reinforced with both jute and glass fibers. They prepared three hybrid ratios and found that adding fibers increased density, impact energy, tensile, and flexural strength, while reducing weight loss due to temperature and water absorption. The composite with more jute absorbed more water and lost more mass at higher temperatures, whereas the higher glass fiber content improved thermal stability. After 1172 hours in water, water absorption was highest in the jute-rich composite (15.8%) and lowest in the glass-rich one (11.7%). In other study by Suchitra and Renukappa [92], the thermal properties of glass fiber-epoxy composites filled with silica, alumina, and alumina trihydrate (ATH) was investigated. Using SEM, they observed good filler dispersion. Their results showed that a hybrid composite with Al_2O_3, SiO_2, and ATH had the best thermal conductivity, glass transition temperature (Tg), and lowest coefficient of thermal expansion (CTE), attributed to strong filler-matrix bonding and enhanced interfacial adhesion, making it the most optimized system.

Moreover, Chinnasamy et al. [93] developed nanoclay-reinforced composites for structural and aerospace applications. Laminates with layers of glass and Kevlar fibers, with 2 wt.% nanoclay, were prepared and tested. Kevlar fibers showed high-temperature peaks (~472°C to 536°C); however, near 800°C, these fibers experienced about 68.8% mass loss. Their findings indicate that hybrid composites with modified Kevlar and glass fibers improved thermal properties and increased Tg without compromising stability.

Khan et al. [94] also investigated the thermo-mechanical enhancement of epoxy by adding carbon and glass fibers. Using hand lay-up and vacuum bagging, composites with various fiber ratios (40:60, 50:50, 60:40) were fabricated. DSC tests showed that both carbon and glass fiber reinforcements significantly increased tensile strength and Tg. Carbon fiber composites showed significantly higher improvements in tensile strength up to 1122% and the glass transition temperature increased from 71°C for neat epoxy to 110°C, making carbon fiber composites overall superior in performance.

6.2. Chemical resistance

Chemical resistance indicates a composite's ability to withstand degradation when exposed to environmental chemicals [95]. Fiber-reinforced polymer composites have superior corrosion [96, 97], chemical [98], and wear resistance [99], along with reduced weight, making them suitable for applications like chemical storage tanks, underground fuel tanks, pickling and plating tanks, chimney stacks, pulp washer drums, and pipelines in the oil, gas, and power industries [100].

In a research, Cousin et al. [101] examined the chemical durability of carbon, basalt, and glass fibers (E and ECR). The fibers were submerged in various environments, such as acidic, saline, alkaline, and deionized water solutions. Carbon fibers proved strongest with minimal mass loss. Basalt fibers resisted acids well but reacted more to alkaline solutions. E-glass fibers showed the least resistance to acid, with 21.9–35.1% mass loss, and also reacted under alkaline conditions. ECR-glass fibers had excellent acid resistance, surpassing basalt. All fibers remained resistant to deionized water, though SEM micrographs revealed chemical reactions and fiber degradation not evident from weight loss alone. In another research, Sharma and Gupta [100] created composites combining aluminum oxide/silicon carbide (1:1) at varying weight percentages, along with E-glass fibers, epoxy resin, and a hardener. They found that composites with higher filler content and voids absorbed more chemicals and acids. The 2 wt% composites demonstrated excellent chemical resistance to various acids such as HCl, HNO_3, and CH_3COOH, as well as solvents like NaOH and Na_2CO_3, and alkalis including benzene, toluene, and CCl_4. This indicates their potential suitability for use in chemical storage tanks.

7. Applications

Glass fiber-reinforced polymer composites are extensively used in engineering structures such as submarines, spacecraft, aircraft, automobiles, and sports equipment due to their lightweight nature, high corrosion, fatigue, fracture toughness, fire resistance, wear, high strength-to-weight ratio, high modulus, and low coefficient of expansion [102].

7.1. Automotive industry

In recent decades, the push for fuel efficiency and vehicle lightweighting has led manufacturers to replace traditional materials like steel with GFRP composites. These composites are used in various forms including strands, woven fabrics, mats, and veils—thanks to their high specific stiffness and strength. Lightweight polymers, enhanced with fillers, improve mechanical, chemical, electrical, and thermal properties while reducing cost and shrinkage, making them ideal for automotive applications [103, 104].

7.2. Construction and civil engineering

FRP composites are increasingly used in civil engineering for reinforcing columns [105, 106], beams [107], and slabs [108] in buildings, bridges, and pavements due to their strength and durability [101].

7.3. Marine applications

Steel has traditionally been used in shipbuilding, but since the 1960s, fiber-reinforced plastics have gained popularity because of their moldability, lightweight nature, and low maintenance. E-glass fiber is most common in marine structures, with FRP sandwich panels and honeycomb bulkheads used to reduce weight. Composites are vital for ship hulls, propellers, turbines, and offshore equipment, offering long service life in harsh, saltwater environments [109, 110].

Studies show that marine components face high stresses from wind, waves, and corrosion. Recent research explores advanced composites for ships, offshore energy, and subsea repairs, highlighting their advantages in durability and weight savings [34]. In a research, Anand et al. [111] studied graphene oxide (GO) in epoxy-based composites for marine environments. After 9 months of seawater and freshwater aging, GO improved water resistance and mechanical properties, even under salty conditions. Micrographs confirmed that GO reduced water sorption and enhanced interfacial bonding, confirming its potential for marine applications. In another research, Fiore et al. [112] investigated steel-reinforced epoxy composites with basalt layers for marine use. Results indicated that adding two outer basalt layers significantly increased strength. Numerical modeling matched experimental results, confirming the benefit of basalt reinforcement, with applications demonstrated on a ship component.

7.4. Sports and leisure products

The sports industry is rapidly growing, relying on advanced materials to improve safety, performance, and sustainability. Fiber-reinforced composites are prominent in sports equipment due to their lightweight, strength, toughness, shock absorption, and ease of use [113-115]. Natural fibers are emerging as sustainable alternatives to synthetic reinforcements, encouraging further research into eco-friendly composites for sports goods. These materials enable lighter, stronger, and more durable sports equipment, improving athlete performance and safety. Applications include structural components, braces, padding, and prosthetics, with ongoing developments aiming to replace traditional materials like wood and aluminum alloys [116].

8. Conclusion

Over recent decades, advancements in materials science have led to the development of hybrid composites aimed at achieving high strength, reduced weight, and lower costs. Since high-strength materials are typically denser and lighter materials usually have lower strength, hybrid composites provide an ideal balance by combining durability with lightweight characteristics.

Author contributions

Hamideh Najafi: Investigation, Writing – original draft, Writing – review & editing; **Behzad Mohammad Khani:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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