



Review article

Crash-proof and sustainable polymer-based composites in modern day transportation systems: A review on fabrication of lightweight components for land, sea and air travels

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ABSTRACT

The need for advanced materials that are lightweight, durable and sustainable in the transportation sector in the recent times cannot be overemphasized. Previously, the focus was solely on endurance and crashworthiness without environmental considerations. However, due to environmental concerns in recent times, researchers are now focusing on lightweight and biodegradable materials that are sturdy, crash-proof, and sustainable. In other to achieve these, when selecting materials for transportation applications, many criteria are typically taken into consideration to cater for the divergence in the environment that the materials will be exposed to in service. Thus, polymer-based materials have been discovered to be appropriate for these purposes based on their inherent qualities such as lightweight, processing flexibility, acceptable properties, availability, economic viability and aesthetics. Therefore, most components of modern-day transportation gadgets and appliances are primarily developed from polymer-based composite materials. This review presents various parts of these gadgets/appliances such as; automotive, ship, train and airplanes that are being used for transportation systems that were produced from polymer-based composite materials. As emerging materials, components from polymer-based composites improve fuel efficiency and promote viable transportation. Hence, the progressive application and future benefits of polymer-based composites as lightweight materials in the transportation industry were the focus of this review. Key policies and regulatory frameworks influencing material selection across different sectors were provided while polymer-based composite materials in different modern day transportation systems like electric cars, naval ships, high-speed trains, and aircraft such as the Boeing 787 were identified and specified.

1. Introduction

Transportation is a dynamic and complex activities that involves the movement of bodies from one location to another. In the recent times and due to more understanding of the differences in geographical locations that usually results in varying environmental constituents or compositions, pollutions, temperature gradient, humidity, topography,

ocean movements and many more, the selection of materials for transportation industries are being faced with various challenges. Hence, the selection of suitable materials for the fabrication of transportation bodies and systems needs critical attention in other to reduce material failure and unwarranted accidents. Thus, transportation sector increasingly seeks and prioritizes the use of materials that provide a balance of high strength and low weight to enhance efficiency, safety, and

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sustainability [1–3]. This heightened emphasis arises from the necessity to improve fuel efficiency, diminish pollutants, and prolong the durability of vehicles, aircraft, and other transportation modes [4–6]. Advanced materials with lightweight are increasingly employed to attain these objectives [7–11]. Consequently, producers and engineers are persistently investigating novel material solutions that deliver enhanced performance while adhering to legal and environmental norms [12,13]. The unique physical and mechanical characteristics of materials are the paramount criterion for their acceptance in these industries [14,15]. Technological advancements and increasing urbanization have heightened the demand for lightweight materials that can aid the movement of goods and services around the world [16,17]. The benefit of lightweight design is to enhance and prolong product's functionality while minimizing its overall weight [18,19]. Application of less dense materials, such as metal foams and composites or decreasing material volume by thinning the walls of critical structural components are two established approaches for mass reduction [20,21]. In both cases, less energy is required to deliver the finished goods, supporting the environmentally benign component of lightweight design [22–24]. The production of lightweight composite structures can incorporate technologies that is based on fibre-reinforced thermoplastic polymers [25–27]. The reduction in weight and the consequent potential cost savings are the key drivers for the use of lightweight materials. By carefully selecting the constituent materials and the orientation of the reinforcing fibres, composites also have the flexibility to be tuned to satisfy design requirements that are inappropriate for conventional materials [28]. This is crucial for performance optimisation because the goal is to reduce mass and/or stress concentrations while maintaining the needed performance. Thus, less fuel will be consumed and fewer greenhouse gases will be emitted due to significant weight savings and enhanced performance [28]. Polymer composites are lightweight materials recognized for their customizable characteristics, rendering them appropriate for diverse applications [29]. Recent studies have increasingly concentrated on reducing environmental impacts, hence, advancing the development of green composites [23,26,30]. Therefore, renewable and sustainable natural fibres are employed to strengthen polymer matrices [31]. Natural fibre-reinforced composites provide benefits like low density, high specific strength, cost efficiency, and ease of processing thereby contributing to the advancement of lightweight materials [32–34]. Plant fibres from flora, fauna, or minerals have elevated cellulose content which enhances their tensile and flexural strengths. In contrast, animal fibres that are abundant in keratin, exhibit natural hydrophobicity, facilitating superior integration with polymer matrices. Oladele et al. [35] discovered that lightweight bio-fibres in epoxy composites offered excellent insulating qualities with improved mechanical strength, wear and moisture resistance which support their suitability for automotive applications [36].

Fabrication of hybrid-based composites is another means of advancing the development of performance specified materials with unusual properties. The characteristics of hybrid reinforced composites are influenced not only by their component materials but also by the stacking sequence and configuration of fibres within the hybrid system [37–39]. The arrangement of fibre layers, whether inner or outer, greatly influences the composite's overall performance, particularly when natural and synthetic fibres are involved. While natural fibres will enhance the lightweight and biodegradability, synthetic fibers will provide the mechanical strengths and improved water resistance. Previous researchers have reported that, hybrid composites featuring a core of natural fibres surrounded by synthetic fibre layers provide enhanced tensile and flexural strengths, stiffness, and water absorption characteristics [32,40–42]. The outer synthetic fibre layers, recognized for their superior strength, enhance the composite's load-bearing capacity, leading to improved mechanical and water absorption properties compared to configurations with natural fibres as the outermost layers [43–46]. In contrast, when synthetic fibres are positioned at the core and encased by natural fibres, the composite exhibits increased water

absorption and swelling due to the hydrophilic properties of natural fibres, which rapidly absorb moisture [47–52]. It has likewise been reported that, the influence of fibre orientation on hybrid composites demonstrates diverse impacts [42]. For instance, composites typically exhibit superior tensile and flexural strengths, together with an elevated tensile modulus, in the longitudinal orientation relative to the transverse orientation [53–56]. Moreover, fibre orientations of 45° have been shown to improve mechanical qualities more efficiently than horizontal or vertical alignments [57–59]. Besides, weight percentage of each fibre type significantly influences the physical and mechanical properties of natural-synthetic fibre hybrid polymer composites. Studies demonstrate that augmenting the ratio of synthetic fibres typically enhances the composite's mechanical, physical, thermal characteristics and water absorption qualities [60–62]. This tendency is due to the integration of high-strength synthetic fibres that demonstrate minimal water absorption properties [63,64]. Owing to these advantageous characteristics, natural-synthetic fibre hybrid reinforced polymer composites find its application in the aerospace, automotive, marine, and railway industries [65]. This paper therefore, present recent studies that have improved the characteristics of polymer composites from different kinds of fibres and polymers, originating from either synthetic or natural, and their applications in the transportation industry. The review examines the selection criteria for crash-proof and sustainable polymer-based composite in transportation sectors which includes, automotive, rail, marine, and aerospace. The impact on lightweight, fuel efficiency, emission reduction and circularity were considered. The main focus was to further encourage blending and synergistic effects of natural and synthetic fibers for the development of polymer-based composites for transportation industry by revealing the benefits and limitations for future needs. Therefore, current developments in material choice, component assembly, and life cycle management approaches with obstacles, trade-offs and policy support mechanisms were provided.

1.1. Comparison of polymer composite materials with traditional materials

Polymer composites serve as better alternatives to traditional materials such as steel and aluminum in manufacturing automotive parts due to their inherent capability to produce lightweight structural components. As presented in Fig. 1, the mechanical properties of composites such as glass fiber-reinforced polymers (GFRPs) and carbon fiber-reinforced polymers (CFRPs) match or exceed those of metals while providing much lighter weight. The tensile strength of CFRPs reaches 1500 MPa, while their flexural strength exceeds 1800 MPa, which exceeds typical values for steel and aluminum. The high strength-to-weight ratio of these materials leads to better fuel efficiency and reduced emissions, which support global sustainability goals. Natural fibre-based composites also provide environmental advantages through their biodegradable nature, reduced energy requirements and carbon emissions despite their lower mechanical strength. The emergence of polymer-based composites allows manufacturers to create intricate shapes and combine multiple parts into one, which decreases the total number of components and makes assembly operations simpler.

2. Application of polymer composites in various transportation systems

This section specifically analyses the applications of various polymer composites in the transportation industry. Many aircraft applications favor the use of polymeric-based materials due to their unique mechanical properties and flexibility in adapting the materials to preferred specifications [28]. These materials can be engineered to have a desired combination of properties, such as low weight, high strength, and resistance to chemical corrosion, making them suitable for use in extreme environments [67,68]. Key advantages of polymer materials over traditional metallic materials include lower thermal expansion,

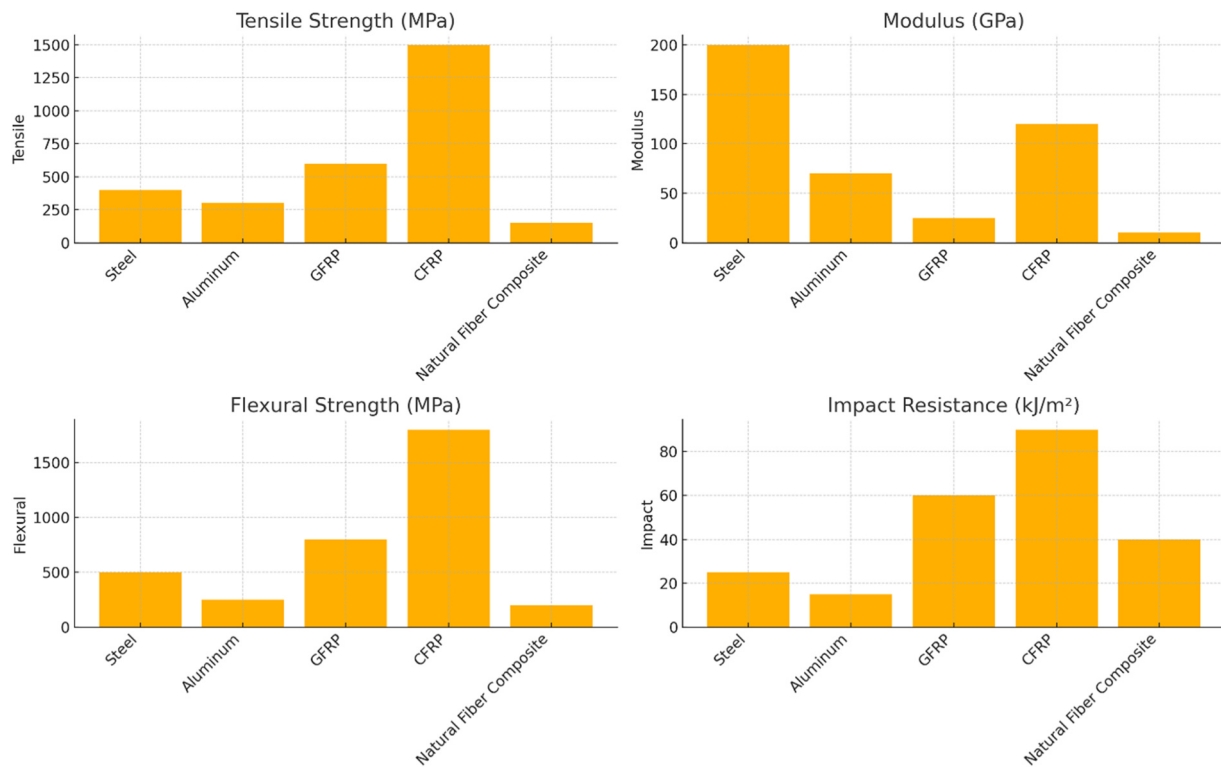


Fig. 1. Mechanical properties of traditional materials and polymer-based composites for automotive applications [66].

excellent fatigue and fracture resistance, dimensional stability, rapid process cycles, and a 20–40 % weight savings [69]. By using polymer composites, for instance, in military fighter planes, manufacturers have been able to reduce their weight by 30 %. Polypropylenes, polyethylenes, and polyamides are all examples of engineering polymers that are replacing more traditional materials in the automotive sector [28]. The use of polymer-based composites has also aided in the enhancement of the aesthetic value of several components of the transportation sector. Another strong factor in support of the application of polymer-based composites in the transportation sector scenario is the high possibility of recycling of the materials, thereby, yielding a high proportion of products that may be reused [70–73]. For certain structural and semi-structural uses, processing optimisation is necessary. For example, the European Union's End of Life Vehicles (ELV) directive [28] mandates that vehicles be made of 95 % recyclable materials; of that number, 85 % must be recoverable through reuse or mechanical recycling, while the remaining 10 % must be recovered through energy recovery or thermal recycling.

Airplanes, ships, cars, lorries, and vans may all have their parts developed to reduce CO₂ emissions by cutting excess weight, improve the efficiency of their production, and recycle their used parts. Nearly 85 % of total life-cycle energy consumption occurs during functional operations [28,65], demonstrating the significance of weight reduction. This is because burning fuel results in the production of force. According to Newton's second law of motion, the easier it is to accelerate something, the less mass it has. Whatever the source of your energy; oil, petrol, diesel, electricity, biofuels, fuel cells, etc, cutting weight is a surefire way to lower your carbon footprint. Due to their superior corrosion resistance, temperature resistance capabilities, high stiffness, strength, and wear qualities, polymers (thermoplastics and thermosets) and polymer composite materials have been increasingly popular in the transportation industry in recent years [14,74]. Polymer composites were only produced during the early stages of industrialisation for use in homes, but as technology advanced, they were increasingly used in the transportation sector [75–77].

In recent times, manufacturing of crucial components for aircraft, spacecraft, rockets, hyperloop shuttles, automobiles, submersibles, ships, and passenger trains uses polymer composites as a separate class of technical materials [78]. Typically, natural or synthetic fibres that have distinctive physico-chemical qualities, characterized by low densities, specific weights, and high strength, are utilised to strengthen polymer materials for transportation applications [79]. The final components of these bodies in the transportation sector are lighter due to their relatively high specific strength and stiffness of polymers and polymer-based composites [77,79,80].

The majority of mass-produced composites utilize polymer matrices, commonly referred to as resin solutions. Various polymers can be created from a wide variety of base materials [81]. There are multiple overarching classes, and within each, there are numerous subclasses. Polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, polypropylene, polyether ether ketone, and several others are among the most often used polymers [82]. Fibres are the most popular kind of reinforcement being used; however, common-ground minerals have also been used [28,83–85]. Polymer matrix composites (PMCs) wide appeal stems from the fact that they can be made cheaply and easily [28]. Low levels of mechanical qualities, such as strength, modulus, and impact resistance, restrict the use of non-reinforced polymers as construction materials. Hence, fabrication of PMCs is made possible by reinforcing polymers with a strong fibrous network. This usually results in PMCs with superior mechanical properties (high specific strength and stiffness; fatigue and impact resistance), good abrasion resistance, low corrosion and cost [28,32,36,86–91]. Nevertheless, their primary drawbacks are a high coefficient of thermal expansion and a low thermal resistance which are still receiving more attention from researchers in the production of advanced materials, basically from composite developments that are gradually being made available in the market [60,92,93]. Honeycomb structures, equipment panels, cylinder support structures, solar array substrates, and antennas are just some of the many important satellite components that make use of polymer composites. Among these was the graphite-reinforced epoxy composites with the use of 30 tonnes

to make the rocket motor boxes for the space shuttle's solid booster. The current research into micrometer-thick sheets may one day make spacecraft with solar sails feasible[14,28]. Gossamer spacecraft applications such as antennas, solar sails, sun shields, radar, rovers, reflect arrays, and solar concentrators necessitate bendable and compliant materials[14,28]. Together with the limited space on conventional launch vehicles, such Gossamer structures can be folded or bundled into tiny compartments. Once in orbit, they can be mechanically, or inflatable expanded into a massive, fully operational, ultralight-weight spaceship. Gossamer structures need to be able to endure for extended periods in a harsh environment where they are primarily subjected to atomic oxygen, ultraviolet, and vacuum ultraviolet radiation[14,28].

Fibres are the principal load-bearing components, and they contribute to the increased stiffness and strength of materials[94–99]. Based on this, fibre-reinforced polymer matrices can benefit from increased protection against environmental dangers and damage [100–105]. Reinforcing polymers with fibres results in a considerable improvement in their structural integrity, which makes them appropriate for use in automotive, aerospace, and marine industries [106–118]. Common examples of synthetic fibres for reinforcements include glass, aramid, carbon, and Kevlar. These materials offer greater strength, hardness, fatigue resistance, and compatibility with structural performance criteria in comparison to monolithic polymer materials [119,120]. However, as a result of always increasing environmental restrictions, there has been an increase in the utilization of natural fibres in the production of components for the transportation industry. Hence, Table 1 present the results of the investigation on the characteristics of some natural fibers that are commonly used as reinforcement materials.

2.1. Common polymers for transportation components manufacturing

To form polymers, monomers are covalently bound together to form larger molecules [14]. The unique molecular structure of polymers that are characterized by a chainlike structure is what gives them their fascinating mechanical capabilities where long strands of monomers form a linear polymer [14,28]. Covalent bonding between the monomers of one chain and those of another creates a three-dimensional network in cross-linked polymers with the entire polymer forming a massive macromolecule [14,28]. On the other hand, polymers can also be broken further based on the chemical nature of the monomers into homopolymers and copolymers. Homopolymers are made up of identical monomers as opposed to copolymers which use a variety of repeated units [127,128]. Based on application, polymer can be classified into thermoset, thermoplastics and elastomers. Fundamentally, in contrast to the extensive cross-linking found in thermosets, elastomers have a looser network structure.

Table 1
Properties of selected natural fibres [36,41,54–56,60,99,101,102,121–126].

Fibre	Density (g/cm ³)	Tensile Strength (MPa)	Elongation (%)	Young Modulus (GPa)
Ramie	1.50	220–938	2.0–3.8	44.0–128.0
Hemp	1.48	550–900	1.6	70.0
Oil Palm	0.70–1.60	50–400	4.0–8.0	0.6–9.0
Sugarcane Bagasse	1.10–1.60	170–350	6.3–7.9	5.1–6.2
Jute	1.30–1.46	393–800	1.5–1.8	10.0 – 30.0
Cotton	1.50–1.60	287–597	3.0–10.0	5.5–12.6
Sisal	1.33–1.50	400–700	2.0–14.0	9.0–38.0
Betel Nut	0.20–0.40	120–166	22.0–24.0	1.3–2.6
Flax	1.40–1.50	345 – 1500	1.2–3.2	27.6–80.0
Coir	1.20	175–220	15.0 – 30.0	4.0–6.0
Bamboo	1.20–1.50	500–575	1.9–3.2	27.0 – 40.0
Kenaf	0.60–1.50	223 – 1191	1.6–4.3	11.0–60.0

2.1.1. Thermoset

Upon curing, thermosetting plastics, also known as thermosets, are polymers that retain their shape indefinitely. These polymers go through an irreversible cross-linking reaction during the curing phase which can be induced by heat, ultraviolet (UV) light or can occur rapidly at ambient temperature[129]. This leads to the formation of a three-dimensional network of covalent connections which prevents molecular chains from moving past one another. As a consequence, the stiffness of the material increases while its creep resistance decreases. When compared to thermoplastics, thermosets are often more brittle [130]. The formation of a stiff structure by the chemical joining of polymer chains is referred to as cross-linking at this point[131]. Glassy thermosets, on the other hand, contain polymer chains that are below the glass transition temperature which causes them to be hard [130]. On the contrary, elastomers possess polymer chains that are above the glass transition temperature and so stay flexible at ambient temperatures. The structure of the polymer is made up of a dense network that is three-dimensional and has permanent cross-links between linear chains [132]. Due to their exceptional strength and resistance to cold flow (creep) at ambient temperature, thermosetting materials are widely utilised in the transportation industry. Usually, heat, radiation, catalysts, or any combination of these techniques can be used to kickstart the curing process for these materials [80]. Epoxies, unsaturated polyesters, phenolics, amino resins (including urea and melamine-formaldehyde), and alkyls are all categories of thermosets that are frequently encountered in the industry[133–135]. There is a significant amount of use for these materials in a variety of industries, including aircraft, ship-building, rail transportation, and automobile manufacturing [136,137].

2.1.2. Thermoplastics

Thermoplastics are semi-crystalline or amorphous materials that can be reprocessed through the application of heat and pressure. They are composed of strong intra-molecular bonds and weak inter-molecular bonds which can be either linear or branched in structure. Unlike thermosetting materials, thermoplastics do not harden when heated [77, 138]. Thermoplastics do not melt or change consistency in a significant form when heated; hence, they can be moulded into practically any shape without difficulty. However, they become rigid and resilient upon cooling. They can be broadly classified as amorphous and semi-crystalline thermoplastics which implies that, crystalline polymers typically include some amorphous components [139,140]. There are lots of polymers that are semi-crystalline rather than purely crystalline or amorphous. Mechanical properties are significantly impacted by the crystalline phase shape. Above their glass transition temperature, crystalline plastics become less stiff, but they will not flow until they reach their crystalline melting point [141]. The properties of crystalline or semi-crystalline polymers at ambient temperatures are superior to those of amorphous polymers in many ways. Amorphous polymers exhibit the characteristics of rigid and unyielding glasses when heated to temperatures below their glass transition temperature. An amorphous polymer, on the other hand, loses its rigidity and becomes pliable when heated above the temperature at which it transits into a glass. In the vicinity of the temperature at which the glass transition occurs, there are significant changes in the mechanical properties of the synthetic polymers. In a wide range of high-performance applications, engineering thermoplastics, which are subsets of synthetic polymers that possess exceptional properties are utilised [127,139,142]. They can be formed into semi-precise structural components and architectural pieces with exemplary formulations. If a part is structurally functioning, it can withstand mechanical forces such as tensile stress, impact, flexure, vibration, sliding friction, severe temperatures, and hostile environments, hence, they are suitable materials for transportation industries [143, 144]. Transparency, self-lubrication and flexible decoration are only some of the benefits of using engineering plastics in place of metal when building a mechanical device. As the price of metals are increasing, polymers are becoming a more attractive alternative due to their

improved physical qualities and operational temperature ranges [145, 146]. Polyethylene, polypropylene, polystyrene, nylon, polycarbonate, polyacetals, polyamide, imides, polyether ether ketone, polysulfone, polyphenylene sulfide, polyether imide, and many more are common examples of thermoplastics that are for transportation industry applications. Common polymers used in the production of transportation components are presented in Table 2 with their properties and costs.

2.2. Application of polymer based materials in automotive

Several nations worldwide have implemented restrictions that limit the industrial use of oil-based raw materials in the production of various

Table 2

Properties and estimated costs for commonly used thermoplastics in transportation industries [80,116,118,121–124,127,129–132,138–153].

Polymer	Density (g/cm ³)	Properties	Cost (\$/ton)
Polybutadiene	0.9	Excellent abrasion resistance, low hysteresis loss, high elasticity	2150–2800
Polypropylene	0.905	Good chemical resistance, good fatigue, and heat resistance	1208
Polyethylene Terephthalate	1.38	High strength, high rigidity and hardness, very low moisture absorption, good creep, and chemical resistance	1900
High-Density Polyethylene	0.941	Low weight, high tensile and impact strength, high resistance to chemicals, and high temperatures.	1216
Polymethyl Methacrylate	1.18	Lightweight, machinability, resistant to salty water, easy recyclability	4821
Low-density Polyethylene	0.91–0.93	High clarity, chemically inert, good impact strength, excellent tear, and stress crack resistance, low cost, low water absorption	1749
Polytetrafluoroethylene	2.2	Exceptional chemical, heat, and low-temperature resistance, good electrical insulating power in hot and wet environments, good resistance to light, UV, and weathering, low coefficient of friction	11777
Polyvinyl Chloride	1.3–1.45	Excellent insulation, high corrosion, shock and abrasion resistance,	1182
Polystyrene	0.96–1.05	Good optical property, good insulation	2213
Epoxy resin	1.2–1.3	High strength, low shrinkage, excellent adhesion to various substrates, low cost, and low toxicity	6341
Polyamide	1.14–1.15	High wear resistance, high thermal stability, and mechanical damping properties, excellent strength and hardness, good sliding and chemical resistance	4803
Nylon 66	1.14	High tensile and flexural strength, high stiffness, excellent heat detection temperature, superior abrasion, and wear resistance	2957

goods. One example of such a law is the European Guideline 2000/53/EG which was implemented by the Commission of the European Union (EU) in 2005 to mandate the utilisation of recyclable materials equivalent to or greater than 85 per cent in the manufacturing of vehicle components [136,154–156]. Consequently, it is anticipated that there will be an increase in demand for sustainable composites which will contribute to a reduction in the weight and cost of vehicles [60]. In addition, the incorporation of lightweight materials is a promising method that has the potential to improve fuel efficiency while simultaneously minimising the impact on the environment in the automobile industry [157–160].

In the process of designing and producing brake levers for automobiles, hybrid reinforced polymer composites, such as glass-kenaf fibres, have been utilised [161]. In the context of automobile bumper applications, comparative research on glass-jute fibre hybrids and synthetic glass fibre composites revealed that a composite material containing 30 % jute and 10 % glass fibres exhibited improved impact strength (11.6 J) and hardness (65.5 HR) compared to traditional glass fibre composites. According to the findings of the study, jute/glass fibre hybrid composites have the potential to serve as viable alternatives to synthetic glass fibre composites for the construction of structural components of automobiles such as bumper beams for example [162].

In subsequent research on the mechanical properties of kenaf/glass fibre hybrid reinforced composites for passenger car bumpers, a comparison was made between these composites and traditional glass mat thermoplastics. In contrast to glass mat thermoplastics, the hybrid composite was found to have a better tensile strength and Young's modulus, but it had a lower impact strength, according to the findings [135,163]. The additional study included the CBT 160 thermoplastic toughening modifier into kenaf/glass fibre hybrid composites [135, 163]. This was done to improve the hybrid composite's resistance to impact and to meet the requirements for bumper applications. An excellent example of incorporating natural fibres into automotive design is the roof structure of the 2017 Mercedes-Benz E-Class. This frame is made up of seventy per cent natural fibre, which results in a fifty per cent reduction in weight when compared to conventional sunroofs that are reinforced with metal [135,163].

To investigate the mechanical performance of kenaf/glass-reinforced epoxy hybrid composites for automotive structural applications, Singh et al. [164] used a fabrication process and conducted an examination. Based on their findings, they discovered that the hybrid composites demonstrated improved tensile and flexural capabilities compared to composites reinforced with pure glass fibre. The fabrication approach was responsible for this improvement, which was attributed to the increased compactness it achieved, thereby, enhancing the interfacial adhesion between the fibres and the matrix. This was supported by the findings of Sapiai et al. [165]. This robust adhesion enabled the effective transfer of tensile and flexural loads. In a similar vein, Yusuff et al. [166] highlighted the fact that the fabrication procedures utilised, in addition to other considerations, have a substantial impact on the mechanical properties of hybrid composites.

The automobile industry, which is concerned with incorporating cutting-edge automotive components into vehicles, is the primary and most common user of polymer-based composite materials [166,167]. In this review, examples of various applications offered throughout the previous years are shown, and a visual summary is provided in Figs. 2–4. It was discovered from Figs. 2–4 that, a higher percentage of automotive parts are from polymer-based composite materials.

Smart and BASF (Germany) have worked together to create a concept automotive that combines cutting-edge innovations in energy efficiency, lightweight construction, and temperature management with remarkable design [14]. This car is a result of the collaboration between the two companies. Since BASF began placing greater emphasis on lightweight materials in the automotive industry in mid-2011, polymer-based composites have played an increasingly essential part in these projects. When it comes to enhancing the efficiency and range of electric vehicles,

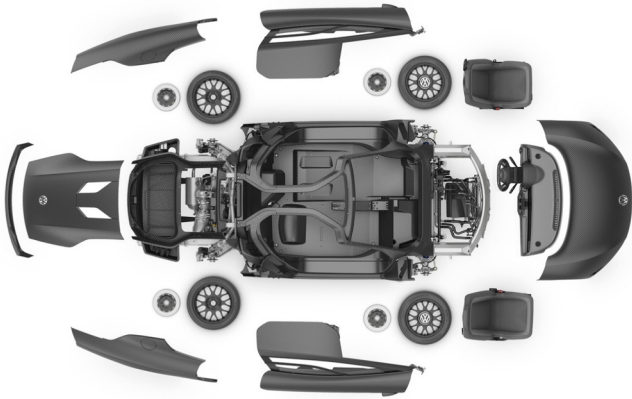


Fig. 2. Volkswagen XL1 carbon fibre body parts (Open access) [168].



Fig. 3. Car interior developed from fibre reinforced polymer composites (open access) [168].

incorporating lightweight materials is necessary. The smart for vision concept features a lightweight metal alternative structure, which considerably increases the vehicle's range. This is one of the most significant improvements introduced by the concept. To manufacture components such as the chassis and outer frame, BASF has developed a specialized technology that makes use of Baxxodur® epoxy systems that are reinforced with carbon fibre [169,170]. By giving qualities that are comparable to those of lightweight metal alloys, carbon fibre reinforcement in high-performance polymers helps to strengthen these materials[170]. To saturate, bond, and further process carbon fibres for automotive component applications, epoxy resin is utilised. This results in the creation of a composite material that has the potential to lower the weight of the chassis by up to 150 % (331 pounds). The Smart Forvision project has made many advancements, one of which is the utilization of polymer wheel rims for mass production. This is the first instance of its

sort anywhere in the world. The Ultramid® Structure which is a high-performance polyamide matrix reinforced with long glass fibres is used in the construction of these rims. This material exhibits high dynamic strength, durability, and toughness, in addition to good thermal and chemical stability. When compared to traditional metal alloy rims, polymer wheel rims are approximately 3 kg (7 pounds) lighter per wheel. This results in a reduction of 12 kg (26 pounds) in the overall weight of the vehicle. The reduction in weight results in an increase in fuel efficiency as well as increase in the positive impact on the environment. To be more specific, the Smart Forvision uses 0.05 litres (0.01 gallons) less fuel and produces 1 g/km (0.003 lb/mile) less carbon monoxide per 100 kilometers (62 miles) than conventional gasoline-powered automobiles[14].

In the meantime, three South Korean companies (LG Hausys, Hyundai Motor, and Shinhan Mold) have joined forces to develop the mass production of composite materials on a global scale. The requirement for metal reinforcements has been eliminated due to the development of a novel battery pack module carrier that is lightweight and designed specifically for electric vehicles. To achieve a construction that is both small and extremely long-lasting, the component is constructed using PA6 polyamide which is supplied by Kolon Plastics and reinforced with carbon fibres that are sourced from Toray Industries in Japan.

When compared to steel in automotive production, PMCs offer the following:[14,171,172]

- i. weight reduction by less than 26 %,
- ii. functional integration and reduction in the number of alloying elements required by almost 91 %,
- iii. high resistance to corrosion and no requirements for anti-corrosion paint,
- iv. high-speed efficiency due to its lightweight,
- v. cost efficiency due to direct compounding and less alloying (no intermediate operations),
- vi. enhanced driving performance due to weight reduction,
- vii. superior recyclability

An industry leader in the production of chemicals, Lanxess has sites in China, Germany (Krefeld-Uerdingen and Hamm-Uentrop), and Belgium (Lillo and Kallo) in addition to having a presence in Wuxi on the Chinese mainland. The company is the largest producer of glass-reinforced thermoplastic polymers in the world, notably in hybrid technology, and it possesses substantial knowledge in the field of plastic-metal composite technology. The research conducted by Puttaraju and Hanumantharaju [173] and Awalellu [174] sheds insight on the growing interest in polymer-based composites that are reinforced with continuous fibres. Lanxess has made an investment of about 120 million dollars in the research and development of high-performance plastics

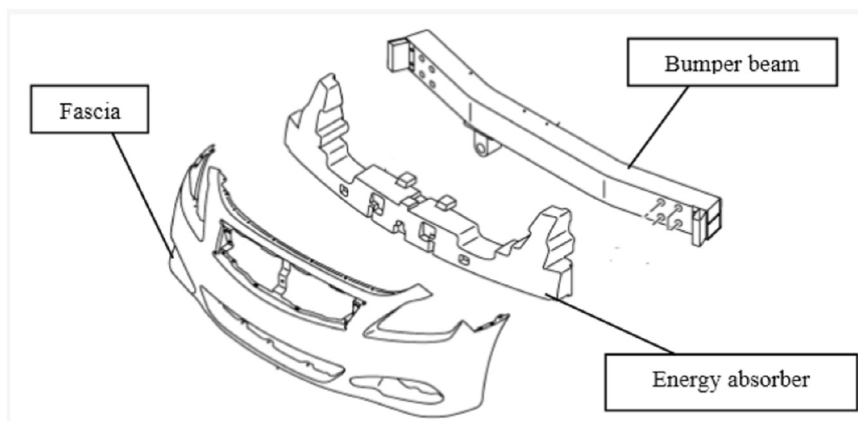


Fig. 4. A schematic of the bumper system (open access) [122].

[174] which is in line with this trend.

The ability of polyamide to form strong interfacial connections with glass fibres is the source of the superior mechanical capabilities of the developed composite materials [174] [175,176]. This capacity enables effective shear load transmission from the matrix to the fibres, which in turn creates superior mechanical qualities. One of the most significant benefits of this technology is its cost-effectiveness. The entire process of injection moulding requires only a single tool, making it more cost-effective than manufacturing components from metal alloys. Polyamide (nylon) composite sheets are utilized in the construction of the hybrid front end of the Audi A8, representing a significant application of this material. These sheets, which are sold by Bond-Laminates GmbH under the brand name Durethan® BKV 30 H2.0 EF, have a high Melt Flow Index (MFI) and include 30 % glass fibres. As a result, they are an excellent choice for incorporation into PA 6 [14]. Bayer Material Science, a subsidiary of Bayer AG in Germany, is credited with being the pioneer in the creation of Bayflex® RIM, a polyurethane material that is efficient in terms of energy consumption to be used in the automotive sector. In light of the fact that industry places a strong emphasis on lowering the weight of vehicles in order to improve electric mobility, the utilization of Bayer's products is pertinent to this purpose. Exceptional surface and paint adhesion, great heat resistance, low moisture absorption, minimal thermal expansion, and outstanding impact resistance are some of the benefits that Bayflex RIM provides. This product is developed with specialized fillers with about 30 % reduction in component weight from this material. A technique known as Reinforced Reaction Injection Moulding (RRIM) is utilized in the manufacturing process. This technique involves the incorporation of fillers and reinforcements into thermoset polymers such as polyurethane and polyurea and, these effectively increasing the range of mechanical capabilities that these polymer-based composites possess [177]. The Roding Roadster, a two-seat sports car, is primarily constructed from polymer-based composite materials. For instance, the chassis' carbon fibre construction guarantees high mechanical characteristics, rigidity, and low mass, all of which are crucial for driving dynamics [178–182]. The braided windscreen frame in this project, which is created from a hollow three-dimensional profile on which the fibres are braided using the form core through RTM resin injection procedures. The shape core constructed of polymer foam can either be removed or left in the element, adding 1.8 kg (4 lbs) of bulk [14].

Similarly, 440 kW (590 HP) French car Citroen DS3 is a special racing vehicle whose components were manufactured from a novel polymer-based composite material reinforced with carbon fibres and Kevlar®. Petter Solberg competed in several European Rallycross Championships in this unusual car. Galway Carbon Motorsport's development team created the polymer composite materials. The acrylic resin Crestapol®1250LV was used as the matrix to create composites and parts for the Citroen DS3. For instance, the nearside doors, the bonnet, and the boot are constructed from this material. Foam was also used to fill the bonnet to increase stiffness while maintaining weight efficiency. Utilizing composites resulted in a significant mass decrease of 82–89 %. For instance, a composite cover weighing 1.8 kg has replaced a steel boot weighing 16 kg (35 lb) (4 lb). Kevlar is used as a reinforcing material because it increases mechanical strength and stiffness and is lightweight [183]. From the foregoing, it was obvious that polymer-based composites are increasingly aiding the desired structural and aesthetic modifications in automotive parts and models from the various components of the automotive applications [184,185]. Most of the new automobile models are made possible by the availability of suitable polymer-based composites for both interior and exterior body parts. Hence, polymer-based composites remain an indispensable material in the automobile industry [74].

2.3. Application of polymer based materials in ship components

Marine components, owing to their environmental conditions, are

always vulnerable to corrosion, which typically results in failures. Carbon steel is predominantly utilised in the construction of various marine structures, including ship hulls. This steel is susceptible to corrosion and changes in long-range electromagnetic and thermal detection. To address these issues, material scientists worldwide are exploring natural and synthetic polymer-based composites as alternatives to steel. Polymer composites have revolutionised the maritime sector by providing lightweight, corrosion-resistant, and high-strength substitutes for conventional shipbuilding materials [186]. These materials augment fuel efficiency, diminish maintenance expenses, and promote vessel performance. Fibre-reinforced polymer (FRP) composites are extensively utilised in military, commercial, and recreational maritime applications, rendering them indispensable in contemporary shipbuilding. Shipbuilding predominantly utilises fibre-reinforced polymers (FRPs), including glass fibre-reinforced polymer (GFRP), carbon fibre-reinforced polymer (CFRP), aramid fibre-reinforced polymer (AFRP), and hybrid composites [187–189]. These materials are utilised in hull structures, decks, superstructures, propellers, rudders, bulkheads, piping systems, storage tanks, and radar masts.

A research investigation on glass/flax fibre hybrid reinforced polymer composites demonstrated an increase in flexural strength and modulus of 90 % and 120 %, respectively. The hybrid composites demonstrated improved ageing durability appropriate for maritime environments, hence, offering a viable alternative to steel [190,191]. A study was conducted to examine the mechanical properties of a woven glass/sugar palm fibre hybrid reinforced unsaturated polyester composite for small boat applications, yielding promising results [192]. Consequently, polymer-based composites provide viable alternatives to metals in ship components. The utilisation of polymer composites in shipbuilding offers numerous advantages, such as substantial weight reduction, corrosion resistance, an elevated strength-to-weight ratio, and enhanced fatigue resistance [191]. These materials provide design versatility, lower maintenance expenses, noise and vibration attenuation, hence, improving operational efficiency and passenger comfort. Their capacity for transformation into intricate forms facilitates new ship designs.

Revolver 42, a speedboat, is the result of a partnership between Michael Peters Yacht Design and the Milan-based firm H30 [193]. Fig. 5 depicts the Revolver 42 speedboat with a vacuum-infused and bonded foam sandwich construction. Crystic® vinyl ester (VE) resins and a carbon fibre-reinforced Corecell™ M-foam core are used to construct the main hull and deck. The dimensions of Revolver 42 are 12.6 m (41 feet) long and 3.4 m wide (11 ft). The use of polymer composite materials benefits sailboats as well. The Sail rocket crew created and constructed the Vestas sail rocket 2 sailboat (Vestas R&D, Isle of Wight, UK). At Walvis Bay in Namibia on November 28, 2012, the Australian sailboat Paul Larson-driven VSR 2 broke the speed record with an average speed of 65.37 knots.

A comparison of two boats with comparable mass with respect to reinforcing fibres and matrix is a good illustration that should be



Fig. 5. Speedboat Revolver 42 (open access) [194].

considered. The first one was constructed using a glass/epoxy composite whereas the second one used a cellulose-reinforced epoxy composite and the boats were submerged completely during the test in 40°C natural seawater. The test's findings demonstrated that both boats' technical specifications and performances were similar [14]. Fig. 6 illustrates the parts developed from polymer composites in the construction of military ships and submarines. To reach a suitable degree of reliability, the military industry needs materials that are extremely reliable, dependable, safe, and robust [195]. Astilleros Santa Pola S.L., a shipbuilding company in Valencia, Spain, in partnership with Aimplas, the Center for Innovation and Technology (CIT), has developed a composite laminate using layers of S-glass fibres blended with aramid fibres and Vacuum Assisted Resin Transfer Molding (VARTM) [14]. Excellent anti-ballistic qualities, UV and corrosion resistance, and low weight are all guaranteed by this combination. This further reduced the weight of the materials used in maritime applications, particularly, for boats with high safety standards like patrol craft. In the most modern destroyer in the US navy which is called the Zumwalt (DDG-1000), named after Admiral Elmon Zumwalt (1900–2000), instead of the usual steel and metal alloys, composite materials were used to lessen their overall weight. Polymer composites were employed to transparently create the ship's radar. The composite superstructure includes masts, antennas, and radars. The deckhouse is entirely comprised of carbon-reinforced vinyl ester resin and was constructed by Ingall's Shipbuilding (USA). Mektech Composites Inc. provided the phenolic fibreglass laminate panels for the roof. This composite was made using phenolic resins because they have great temperature resistance and fire-retardant qualities that are sufficient to meet the Navy's fire requirements [14].

2.4. Application of polymer based materials in train components

In the 1950s, the railway industry used polymer-based composite material for the first time in interior parts like seats, luggage compartments, toilets, and other essential features [196]. In addition to the composite's advanced development, certain fundamental structures have also begun to utilize polymer-based composite as indicated in Fig. 7 [197–203]. Polymer composites are essential in contemporary train manufacturing, providing benefits such as decreased weight, improved durability, and resistance to environmental deterioration. These materials, chiefly fibre-reinforced polymers (FRPs) such as glass fibre-reinforced polymer (GFRP) and carbon fibre-reinforced polymer (CFRP), are utilised in several train components. Primary uses encompass train body structures, wherein polymer-based composites facilitate weight reduction, hence, enhancing fuel efficiency and velocity. Interior elements, including seating, flooring, and paneling, gain advantages from fire resistance, acoustic insulation, and aesthetic versatility. Structural components such as doors, windows, and roofing employ polymer-based composites for their impact resistance and lightweight characteristics. Moreover, electrical enclosures and insulation materials in trains utilize the non-conductive and corrosion-resistant properties of composites.

The main factors influencing the use of polymer-based composite materials are the enhancement of vehicle performance regarding speed, energy efficiency, noise, vibration, and harshness (NVH). Instances of trains employing polymer-based composite structures include the Tilting Train eXpress (TTX), Automatic Guided Transit, and a bimodal train in Korea. The safety aspect has been paramount in the creation of these trains owing to velocity considerations [204]. A primary concern is the aerodynamic shockwave where once the train enters the tunnel, the situation deteriorates. A compressive wave is generally generated at the

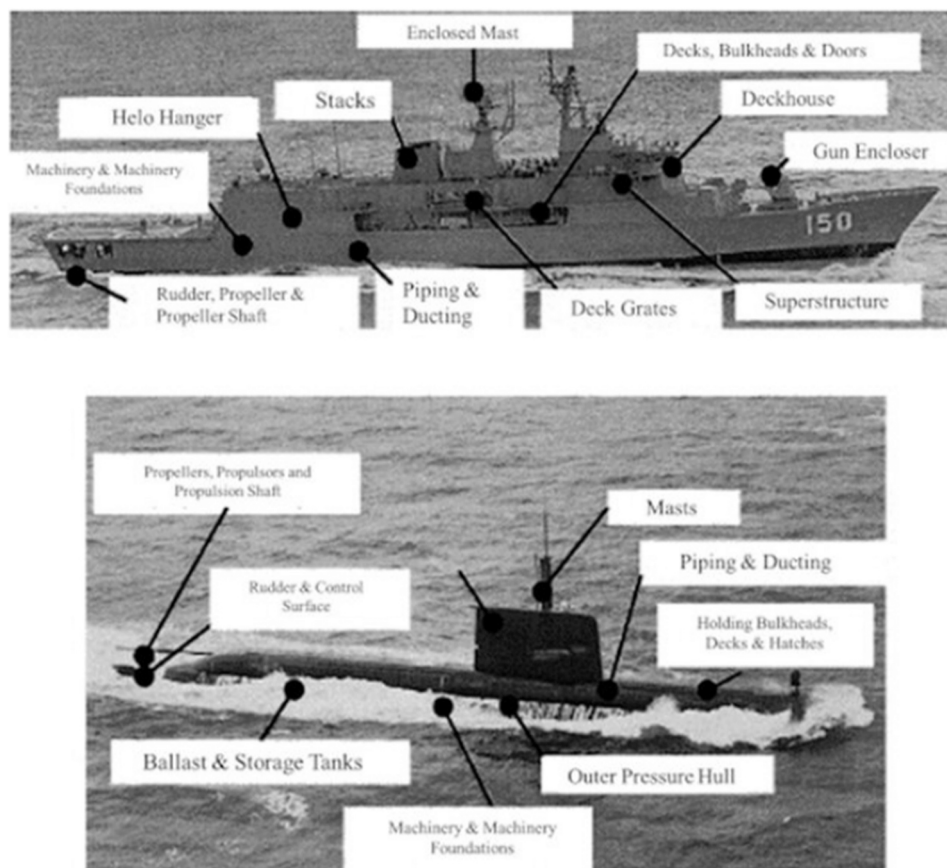


Fig. 6. Reinforced polymer structures in naval ships and submarines [191].

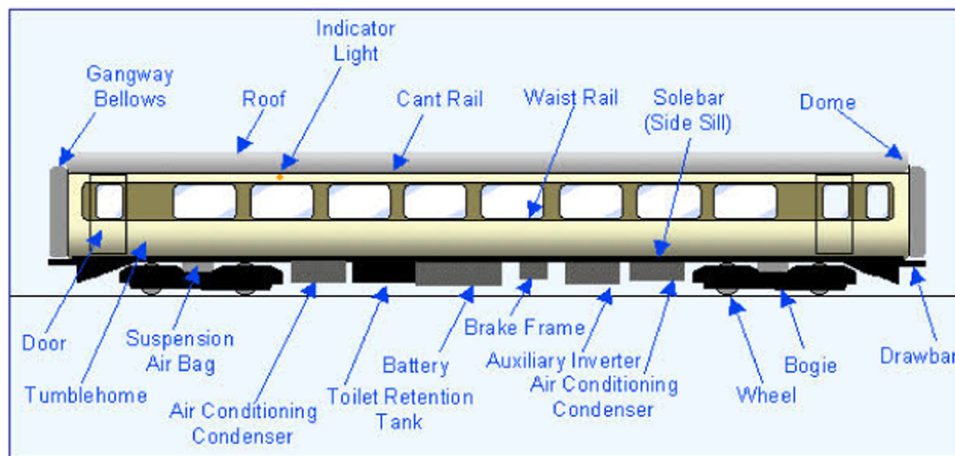


Fig. 7. Exterior parts of passenger trains developed by polymer composites interlinked with other materials (open access) [196].

entrance and travels to the tunnel exit. This situation puts a lot of strain on the tunnel and railway infrastructure. The ideal cross-sectional area distribution of a high-speed nose was investigated by Ku et al. [204]. The complex profile was created to optimize nose lengths of 5, 7, 10, 12 and 15 m. By improving the nose shape, the study sought to reduce the micro pressure that develops after a train exits a tunnel. The vehicle drag is decreased along with the shockwave. The problem might be resolved through the use of composite technology. Thus, polymer-based composite fabrication is an effective way to approach the challenging nose profile. The advantages of using polymer-based composite materials for train noses include cost-effectiveness and the ability to shape the complex design more readily and smoothly than when using metal sheets.

FRP composite is used in the design and manufacture of rail vehicles not only for the creation of the complex skin on its nose but also for other mechanical components [205]. It is also employed undoubtedly based on its mechanical strength and lightweight [143]. Many have conducted extensive research that has been widely supported by the process. Other important studies, such as those on the manufacturing impact on the vehicle safety structure, the natural frequency of polymer-based composite bogie frames, the structural behavior under critical loading, and the dynamic behavior of polymer-based composite wheel sets of the railway vehicle have been carried out to demonstrate the reliability of polymer-based composite materials [206].

2.5. Application of polymer based materials in airplane components

Polymer composites are essential in contemporary aircraft building, providing substantial benefits compared to conventional materials such as aluminium. These materials, chiefly fibre-reinforced polymers (FRPs) like carbon fibre-reinforced polymer (CFRP) and glass fibre-reinforced polymer (GFRP), offer elevated strength-to-weight ratios, corrosion resistance, and enhanced fuel efficiency. Polymer composites are widely utilised in numerous aircraft components, such as fuselage sections, wings, tail structures, landing gear doors, and interior panels [145,146,207]. CFRPs are preferred for structural components because of their low weight and exceptional mechanical qualities which improve aerodynamics and reduce fuel consumption. Composite materials enhance resilience to fatigue and environmental influences, hence, extending service life and decreasing maintenance expenses. The primary advantages of employing polymer composites in aeroplanes are weight reduction, which improves fuel efficiency, enhanced durability, and increased design freedom. Nonetheless, obstacles include elevated production expenses, complex fabrication procedures, and recycling concerns. Current research aims to develop economical and sustainable composite materials to enhance their use in aircraft engineering [208]. The various components of an airplane made of fibre-reinforced polymer

composites are seen in Fig. 8. By reducing the weight of each aircraft produced by just 1 pound, airplane production companies may save up to 11,000 gallons of gasoline annually [203]. As aircraft manufacturers increasingly emphasise efficiency and sustainability, polymer composites will persist as a crucial material in the future of aviation technology.

The first manufacturer of components strengthened with carbon fibres for civil aircraft was a Russian R&D business called AeroComposit which lately concentrated on integrating contemporary technologies into Russian aircraft technology. The final idea involved using a composite made by combining carbon fibres with a newly created and cost-effective resin. Recent projects include the NH90 helicopter fuselage, A380 wing spoilers, and A400M VTP tip. The Airbus A380's wing spoiler chipset is made up of 16 components that are separated into two groups of 8 each which are positioned in a different wing and are mirror images of one another. The material structure can be described as a composite sandwich box comprised of M21-prepared resin systems and T700 carbon fibre reinforcement arranged in a honeycomb pattern [210].

The Boeing B-787 Dreamliner is considered a groundbreaking advancement in the aerospace sector, utilizing sophisticated materials and contemporary engineering methods. The advanced design, sophisticated engines, utilization of lightweight composite materials, and diminished noise levels markedly improve onboard comfort [211]. About 80 % of the aircraft's volume is comprised of polymer matrix composites (PMCs) which account for roughly 50 % of its overall mass. Additional materials utilised in its construction are steel (10 %), titanium alloys (15 %), aluminium alloys (20 %), and various components (5 %) [212,213]. The fuselage, wings, and tail are predominantly fabricated from polymer-based composite materials [214]. Moreover, the Dreamliner has "sandwich" laminate constructions fortified with carbon fibres. These laminates feature a honeycomb core encased between two slender outer layers, offering exceptional stiffness, elevated impact strength, and superior corrosion resistance. This design lowers operational expenses, streamlines the fabrication of intricate structures, decreases the component count, and expedites assembly. The aeroplane utilizes HexMC carbon-epoxy composites, manufactured by Hexcel (USA), which provide weight reduction while preserving superior mechanical strength and stiffness [215]. Elements include window frames, brackets, fittings, studs, and intercostals of the Dreamliner are constructed with HexMC components [203,216,217].

Victrex Europa GmbH provides composite materials for aerospace applications, presenting a sophisticated alternative to traditional metal alloys. VICTREX® PEEK (polyetheretherketone) is a linear, aromatic, semi-crystalline polymer that is part of the polyaryletherketone (PAEK) family. In comparison to metal alloys, these composite materials demonstrate superior specific strength and reduced density, while preserving similar mechanical strength and dimensional stability.

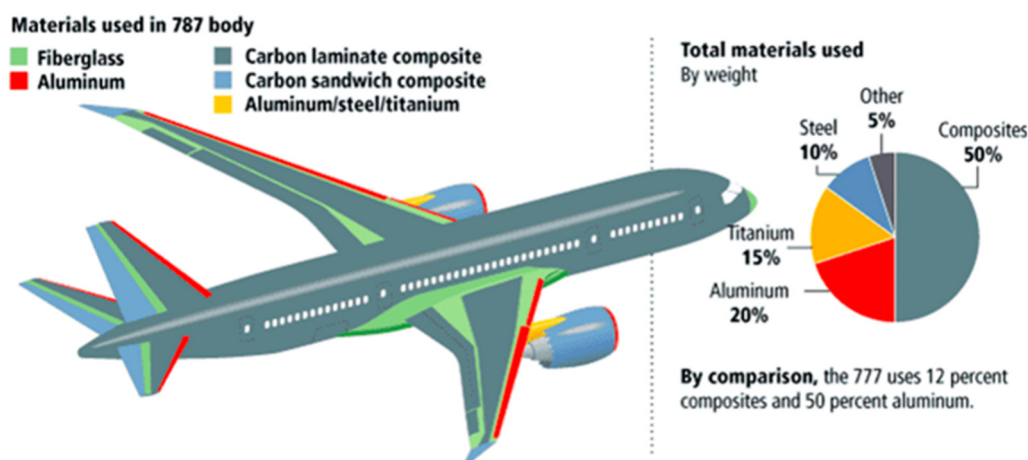


Fig. 8. Overall distribution of composite materials used in Boeing 787 aircraft (open access) [209].

Furthermore, VICTREX® PEEK tolerates mild to elevated temperatures, exhibits corrosion resistance, and withstands exposure to aggressive chemicals. Possessing a melting point of 343 °C (649 °F), it exhibits superior wear and abrasion resistance. The shift from metal alloys to high-performance polymers has been recognized as an economic strategy for decreasing component manufacturing expenses. To improve the mechanical properties of VICTREX® PEEK-based composites, reinforcements including chopped glass fibres, chopped carbon fibres, and high-modulus carbon fibres have been included. The wings and tail structure of the aircraft are predominantly composed of carbon-epoxy composites [203,216,217]. The aircraft's lower integrated skin, comprising spars, ribs, and stringers was produced with composite materials and cured in an autoclave at 175°C (347 °F) under a pressure of 7 bar (102 psi). The primary aim of this methodology was to attain substantial weight reduction. Polymer-based composite components weigh roughly 25 % less than comparable metal alloy components.

High-performance thermoplastic materials were employed for the aircraft's food tray arms to enhance lightweight applications. The designs utilised SABIC Innovative Plastics' Ultem® PEI (polyetherimide) resin in conjunction with carbon fibres, yielding composite materials with a carbon fibre content of 30–40 %. Finite element analysis (FEA) and mould flow analysis (MFA) were performed with Abaqus software to assess internal stresses for optimal mechanical performance. The design choices yield an estimated yearly reduction of 0.5 million gallons of fuel and a decrease of 9.9 million pounds of CO₂ emissions for an airline operating around 600 aircraft, each with an average seating capacity of 200 passengers[218]. Additionally, a recent partnership between OAK AeroComposites and FACC (Austria) sought to create an ultralight composite wing for the MS-21 aircraft, underscoring the industry's ongoing commitment to weight reduction and enhanced fuel efficiency.

3. Summary of specific parts of polymers in automotive, ship, train, and airplane applications [219–228]

Tables 3–6 presents an extensive overview of automotive components that utilises composites in modern days applications. The section explains the components along with composite types and performance advantages to demonstrate the increasing adoption of lightweight and durable materials over traditional materials. Also presented was how automobile manufacturers use these materials to boost efficiency and decrease emissions while advancing sustainability objectives in contemporary vehicle production.

3.1. Percentage of composite materials usage in transportation industry

The modern transport industry employs polymer composites

Table 3
Automobile.

Component	Composite Type	Matrix/Fiber Used	Key Benefits	Real-World Examples
Bumper beams	Glass fiber-reinforced polymer (GFRP)	Epoxy / Glass fiber	High impact resistance, weight reduction	Toyota Prius, BMW i3
Door panels	Natural fiber composite	Polypropylene / Hemp fiber	Lightweight, biodegradable	Mercedes-Benz A-Class
Roof structure	Carbon fiber-reinforced polymer (CFRP)	Epoxy / Carbon fiber	High strength-to-weight ratio	Mercedes E-Class Coupe
Dashboard	Hybrid natural-synthetic composite	Polypropylene / Kenaf + glass fiber	Noise reduction, sustainability	Toyota Lexus
Interior trim	Natural fiber-reinforced plastic	Polypropylene / Flax	Thermal insulation, recyclability	Ford Focus

Table 4
Ships.

Component	Composite Type	Matrix/Fiber Used	Key Benefits	Real-World Examples
Hull panels	GFRP	Polyester / Glass fiber	Corrosion resistance, low maintenance	Wavelength 35 patrol boat
Deck structures	CFRP sandwich	Epoxy / Carbon fiber	Lightweight, fatigue resistance	Sunreef Yachts
Superstructure	Foam core composite	Vinyl ester / Glass fiber	Weight savings, vibration damping	HSC Francisco ferry
Rudders	GFRP	Epoxy / Glass fiber	Hydrodynamic performance	Custom sailing yachts
Propeller shrouds	Hybrid composite	Epoxy / Carbon-glass hybrid	Noise reduction, strength	Naval research vessels

throughout body panels, interiors, structural components and miscellaneous parts. Fig. 9 describes the percentage of composite materials distributed across transportation industry. The aerospace industry applies about 40 % of composites in body components and 15 % in interior

Table 5
Train.

Component	Composite Type	Matrix/ Fiber Used	Key Benefits	Real-World Examples
Bogies	CFRP	Epoxy / Carbon fiber	Weight reduction, energy efficiency	Shinkansen prototype
Sidewalls	GFRP	Polyester / Glass fiber	Corrosion resistance, lightweight	Siemens Velaro
Roof panels	Natural fiber composite	PP / Flax fiber	Eco-friendly, thermal insulation	Alstom Coradia iLint
Interior floor panels	GFRP	Epoxy / Glass fiber	Durability, weight saving	Bombardier Talent
Driver cabins	Hybrid composite	Phenolic / Carbon-glass mix	Fire resistance, structural strength	Hitachi AT300

Table 6
Airplanes.

Component	Composite Type	Matrix/ Fiber Used	Key Benefits	Real-World Examples
Fuselage	CFRP	Epoxy / Carbon fiber	High stiffness, lightweight	Boeing 787 Dreamliner
Wings	CFRP	Epoxy / Carbon fiber	Fuel efficiency, aerodynamic performance	Airbus A350 XWB
Tail structures	CFRP	Epoxy / Carbon fiber	Weight saving, high strength	Bombardier CSeries
Floor beams	Glass-carbon hybrid	Epoxy / Glass + Carbon fibers	Balanced cost and weight	Gulfstream G650
Nose cone	GFRP	Epoxy / Glass fiber	Radar transparency	Dassault Falcon 7X

components due to the need for weight reduction and fuel efficiency. The automotive industry uses composites more extensively in interior components (35 %) while applying them moderately in structural elements (20 %). Trains and ships demonstrate comparable patterns of composite utilization in their structural and interior sections, although their percentages remain slightly lower. This demonstrates how

transportation industries are adopting lightweight, durable and eco-friendly materials at an increasing rate. The comparison demonstrates how polymer-based composites serves as strategic components to boost performance while decreasing emissions, fulfilling modern sustainability requirements and regulatory needs.

3.2. Industrial and commercial automotive models using polymer-based composites

Table 7 presents various types of polymer composites that have been successfully integrated into industrial and commercial automotive models. It further demonstrates the industry’s growing trend toward lightweight, sustainable materials through real-world applications such as carbon fiber roofs and natural fiber interiors, and composite fuse-lages. The examples show the current applications of composites being used to improve performance while reducing emissions and fulfilling changing regulatory and consumer requirements across the worldwide transportation industry.

4. SWOT analysis of natural fiber-reinforced composites in the transportation industry

To systematically evaluate the feasibility of natural fiber-reinforced composites (NFRCs) in transportation, a SWOT analysis was conducted (Table 8) This section conducts a SWOT analysis of natural fiber-reinforced composites in transportation to demonstrate their potential as sustainable alternatives to conventional materials. The growing demand for environmentally friendly solutions makes these composites attractive because they possess lightweight properties and biodegradable characteristics. The analysis considers both internal limitations and external obstacles that affect these composites. The analysis further examines internal strengths and weaknesses, together with external opportunities and threats, which determine their future development in modern transport applications.

4.1. Impact of composites on transportation bodies weight reduction and fuel efficiency

The section displays an infographic effects of polymer-based composite materials on weight reduction and improvement of fuel efficiency in major transportation systems, including automobiles, trains, ships,

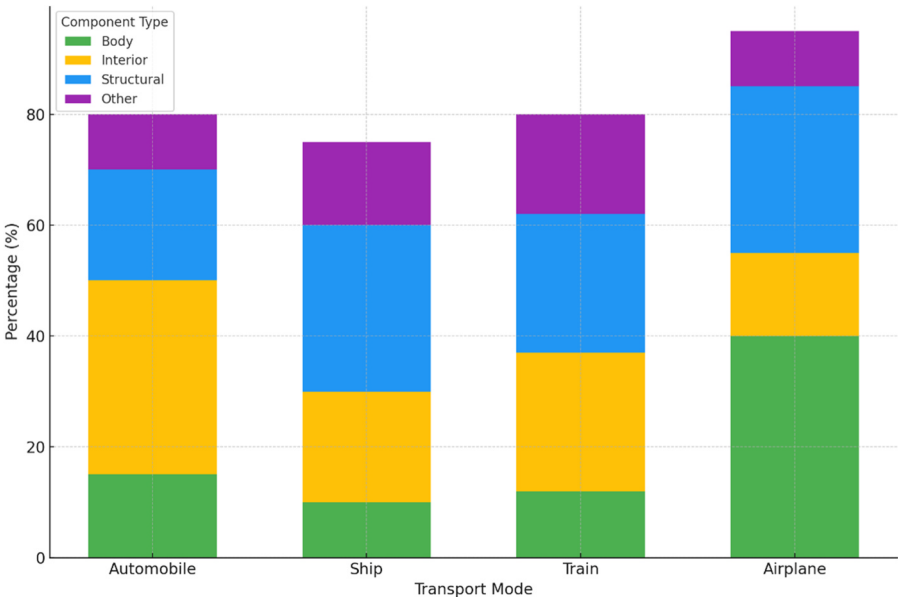


Fig. 9. Percentage of Composite Materials in the Transportation Industry [229].

Table 7
Different types of composites used in industrial and commercial automotive models.

Vehicle/Model	Component	Composite Type	Key Benefits
Mercedes-Benz E-Class Coupe	Roof panel	CFRP	Weight reduction, increased rigidity
Citroen DS3	Doors and bonnet	Natural fiber-reinforced composite	Sustainability, lightweighting
BMW i3	Passenger cell	CFRP	High crash safety, reduced weight
Audi A8	Front-end carrier	Hybrid glass-carbon composite	Crash energy absorption, stiffness
Toyota Prius	Interior panels	Natural fiber-reinforced plastic	Eco-friendliness, cost efficiency
Chevrolet Corvette Z06	Chassis floor	CFRP	Rigidity and weight reduction
Lexus CT 200 h	Interior door trims	Kenaf-reinforced PP	Noise absorption and sustainability
Ford Focus	Underbody shield	Glass fiber-reinforced PP	Durability and corrosion resistance
Porsche 911 GT3 RS	Hood	CFRP	Weight savings and speed optimization
McLaren P1	Monocoque chassis	CFRP	Extreme lightweight and strength
Nissan Leaf	Dashboard	Natural fiber composite	Eco-design and recyclability
Jaguar XE	Front bumper beam	GFRP	Impact absorption and lightweighting
Honda Civic	Seat backs	Natural fiber/PP	Weight saving and biodegradability
Mazda MX–5	Hardtop	CFRP	Weight reduction and strength
Volkswagen Golf	Engine cover	GFRP	Heat resistance and weight saving
Boeing 787 Dreamliner	Fuselage and wings	CFRP	Fuel efficiency, structural integrity
Airbus A350	Primary structures	CFRP	Weight saving, corrosion resistance
Bombardier CSeries	Tail structure	CFRP	Improved aerodynamics, weight reduction
Embraer E2 Jets	Wing components	CFRP	Reduced drag and weight
Gulfstream G650	Floor beams	Glass-carbon hybrid	Balanced cost and weight
Dassault Falcon 7X	Nose cone	GFRP	Radar transparency
Airbus A220	Center fuselage	CFRP	Durability and fuel saving
ATR 72	Horizontal stabilizer	CFRP	Stability and reduced maintenance
Lockheed Martin F–35	Body panels	CFRP	High strength-to-weight ratio
Airbus A320neo	Engine nacelle	Glass-carbon epoxy	Weight efficiency and fire resistance
Alstom Coradia iLint	Interior panels	Natural fiber composite	Biodegradability, reduced emissions
Bombardier Talent	Flooring	GFRP	Durability and weight saving
Siemens Velaro	Sidewalls	GFRP	Corrosion resistance, lightweight
Hitachi AT300	Driver cabins	Phenolic/carbon-glass	Fire resistance and strength
Shinkansen Alfa-X	Bogies	CFRP	Weight and noise reduction
CAF Urbos	Ceiling panels	GFRP	Easy maintenance and modularity
Stadler FLIRT	Wall panels	Natural fiber-reinforced polymer	Environmental compatibility
Talgo Avril	Roof panels	Glass fiber epoxy	Lightweight and aerodynamic shape

Vehicle/Model	Component	Composite Type	Key Benefits
CRRC High-Speed	Underframe	GFRP	Corrosion and fatigue resistance
Hyundai Rotem EMU	Interior panels	Thermoset/glass fiber	Thermal and mechanical stability
Sunreef 60	Hull and deck	GFRP sandwich	Durability, reduced maintenance
HSC Francisco	Superstructure	Foam core composite	Vibration damping and strength
Patrol Boat Defender Class	Hull	GFRP	Corrosion resistance and stealth
Princess Y85 Yacht	Hull shell	GFRP	Luxury performance and lightweight
B&Oteau Oceanis 51.1	Deck	Glass/polyester	UV and corrosion resistance
Naval Research Vessel	Propeller shrouds	Carbon-glass hybrid	Noise and wear resistance
SeaCat Ferries	Cabin modules	GFRP	Lightweight modular design
Jeanneau Sun Odyssey	Rudder	GFRP	Hydrodynamic performance and rigidity
IMOCA 60 Sailing Yacht	Keel	CFRP	High load endurance
Catana 53	Bridge deck	Sandwich composite	Weight saving and buoyancy
Mercedes Citaro	Side panels	GFRP	Lightweight, corrosion resistance
Volvo 7900 Electric	Roof battery cover	GFRP	Fire resistance, ease of assembly
BYD K9	Front fascia	Glass fiber/epoxy	Aerodynamic and cost-effective
Solaris Urbino 12	Interior panels	Natural fiber composite	Noise damping, eco-design
MAN, Lion&City	Flooring	GFRP	Load distribution, weight savings

Table 8 SWOT analysis.			
Strengths	Weaknesses	Opportunities	Threats
Renewable and biodegradable source materials	Lower mechanical properties compared to synthetic fibers	Growing demand for sustainable and eco-friendly materials	Competition from advanced synthetic composites (e.g., CFRP)
Low density and good specific strength	Moisture sensitivity leading to dimensional instability	Government policies supporting green materials (e.g., EU ELV Directive)	High processing costs in scaling for high-performance applications
Reduced environmental impact compared to synthetic composites	Inconsistent quality due to natural variability	Innovation in surface treatment and hybridization techniques	Lack of standardization and regulatory approval in certain sectors
Good acoustic and thermal insulation properties	Limited thermal resistance	Lightweighting targets in electric vehicle design	Potential supply chain issues due to crop variability
Lower energy consumption in production	Poor interfacial bonding with certain polymer matrices	Integration into circular economy strategies in transportation	Resistance from traditional manufacturers and stakeholders

and airplanes. The representation in Fig. 10 demonstrates how polymer composites create weight reductions in vehicles which leads to better fuel efficiency and decreased environmental emissions, expanding sustainability targets for the global transportation industry. The weight reduction of automobiles through composite materials reaches 30 %

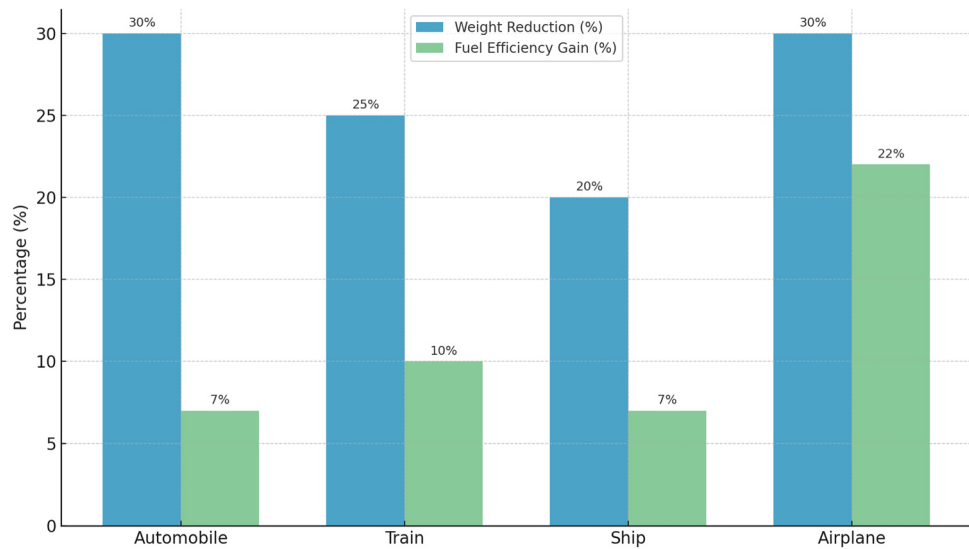


Fig. 10. Impacts of Composites on Weight Reduction and Fuel Efficiency [230].

which leads to a 7 % improvement in fuel efficiency. Likewise, airplanes reduce their weight by 30 % which leads to a 22 % decrease in fuel consumption. The weight reduction of 25 % in trains and 20 % in ships results in fuel efficiency improvements of 10 % and 7 %, respectively. The data illustrate how composites function as essential components for sustainable transportation systems.

5. Influence of policy drivers on materials choice for various transportation systems

This section identifies essential worldwide and local policy elements that affect material choices throughout different transportation industries. Global and regional policies such as the EU ELV Directive, together with CAFE standards and IMO decarbonization strategies, encourage manufacturers to adopt lightweight sustainable materials that are also recyclable. Table 9 presents these policies through a brief chart to demonstrate how regulatory frameworks drive prompt adoption of polymer composites and natural fiber-reinforced alternatives across the automotive, ship/marine, train/rail and airplane/aerospace industries.

6. Future trend and justification

The world as a global community is dynamic and circular in its entirety with several activities going on naturally. Human activities were encompassed within these global ones and their influence has been a major concern in the dynamic nature of the world. More recently, many technological advancements in materials design have triggered the circular economy in the world in a continuous trend [196]. Transportation of humans and resources globally is increasing daily due to an increase in human needs and awareness. Hence, the role of transportation from one location to another cannot be downplayed. More attention still needs to be given to the development of materials for the transportation of more goods and services in more convenient and affordable conditions. Since it has been established that polymer-based materials are indispensable in this drive, hence, more advanced materials are to be developed from the several opportunities emanating from polymeric materials. Presently, a higher percentage of transportation systems’ components are made from polymer-based materials, and the trend is ongoing as more products are being developed with improved properties.

The transportation industries facilitated the movement of individuals and commodities by automobiles, trains, aircraft, and ships, among

Table 9
Influence of policy drivers on materials choice for different transportation systems.

Sector	Policy / Standard	Region	Core Targets Relevant to Materials	Practical Impact on Composite Adoption
Automotive	End-of-Life Vehicles (ELV) Directive 2000/53/EC	EU	≥ 95 % reuse/recovery, 85 % material recycling; bans Cd, Pb, Hg, Cr ⁶⁺	Favors recyclable natural-fiber/thermoplastic composites over metal-plastic hybrids
Automotive	CAFE/GHG & fuel-economy rules (MY 2027–31)	USA	Fleet avg ≥ 50 mpg by 2031; rising penalties for mass	Drives CFRP, GFRP, and bio-composites to cut curb weight
Automotive	Stage IV CAFC + NEV dual-credit scheme	China	10 % tighter fuel limits from 2026; CAFC linked to EV credits	Encourages lightweight natural-fiber PP, GMT door panels, etc.
Marine	IMO 2023 GHG Strategy + EEDI/EEI	Global	–40 % carbon-intensity by 2030; ≥ 5 % zero-carbon energy share	Promotes lower displacement composite hulls/superstructures
Rail	EN 45545–2 Fire-Safety Standard	Europe (also Asia)	Strict HL1–HL3 limits on flame spread, smoke & toxicity	Pushes phenolic/intumescent FRP interiors and sandwich exteriors
Aerospace	14 CFR Part 25 + FAA AC 20–107B	USA / EASA	Demonstrate damage-tolerance & flammability compliance for composites	Accelerates certified CFRP/PEEK wings, fuselage skins, and NF side-walls
Cross-sector	REACH hazardous-substance limits	EU (global supply chain)	Authorization/ban of SVHC chemicals in polymers	Spurs shift to bio-resins and halogen-free FR additives in composites
Cross-sector	“Fit-for-55” CO ₂ standards for HDVs & aviation + CORSIA	EU / ICAO	15–30 % CO ₂ cuts for trucks/planes in 2030; carbon offsetting	Rewards mass-reduction—NF panels, thermoplastic CFRP floor beams

other modalities, across land, air, and sea. Advanced transportation systems generally employ non-renewable fibre-reinforced composite materials such as Kevlar, graphite, Spectra, glass fibre, aramid, carbon nanotubes, and Zylon. Nonetheless, the world is evolving, and sustainable materials are at the forefront since inorganic resources such as petroleum and other mineral sources are depleting. Consequently, by transitioning to bio composite materials and addressing the requirements of each category of transport vehicles, it is feasible to meet the sustainability demands within the transportation industry. Relocating certain heavier components enables high-performance natural fibre composites to reduce transport weight, thereby decreasing fuel consumption and CO₂ emissions. Also, nano and powder technology as well as additive manufacturing should be adopted into the development of hi-tech materials. More natural and recycled materials are to be developed for use in transportation industries to aid green and sustainable eco-friendly materials needed for future development.

7. Conclusion

Applications of polymer-based composite materials in transportation industries have been considered in this review, where it was discovered that polymer-based components represent higher proportions of the transportation industries structurally. The justification for this was based on the inherent properties of the constituents. Hence, continuous blend of natural and synthetic fibers as reinforcements in polymer matrix are to be advanced further based on the possibilities of achieving crash-proof, lightweight and sustainable materials. Partial replacement of synthetic fibers with natural fibers are recommended for advanced and high-performance composite materials in transportation industries without exception. This will help to achieve materials with optimum properties that can withstand the fluctuation or unstable environmental conditions that they are subjected to in service. Modern transportation systems have been made possible due to improved polymer-based composites with several models of transportation facilities based on the availability of suitable polymer based composite materials. Therefore, more progress is still being envisaged in polymer-based composites for transportation industries. This is essential because polymer has been discovered as the most suitable material for this application in terms of properties and cost.

Author contribution

All authors contributed equally to the write-up and revision of this work

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article

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