C Journal of Carbon Research

Review

Carbon Fibers: From PAN to Asphaltene Precursors; A State-of-Art Review

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Abstract: Due to their outstanding material properties, carbon fibers are widely used in various industrial applications as functional or structural materials. This paper reviews the material properties and use of carbon fiber in various applications and industries and compares it with other existing fillers and reinforcing fibers. The review also examines the processing of carbon fibers and the main challenges in their fabrication. At present, two main precursors are primarily utilized to produce carbon fibers, i.e., polyacrylonitrile (PAN) and petroleum pitch. Each of these precursors makes carbon fibers with different properties. However, due to the costly and energy-intensive processes of carbon fiber production based on the existing precursors, there is an increasingly growing need to introduce cheaper precursors to compete with other fibers on the market. A special focus will be given to the most recent development of manufacturing more sustainable and cost-effective carbon fibers derived from petroleum asphaltenes. This review paper demonstrates that low-cost asphaltene-based carbon fibers can be a substitute for costly PAN/pitch-based carbon fibers at least for functional applications. The value proposition, performance/cost advantages, potential market, and market size as well as processing challenges and methods for overcoming these will be discussed.

Keywords: asphaltenes; carbon fiber; PAN; pitch; precursor

Citation: Bisheh, H.; Abdin, Y. Carbon Fibers: From PAN to Asphaltene Precursors; A State-of-Art Review. *C* **2023**, *9*, 19. https://doi.org/10.3390/c9010019

Academic Editors: Olena Okhay and Gil Gonçalves

Received: 22 December 2022
Revised: 23 January 2023
Accepted: 28 January 2023
Published: 4 February 2023

1. Introduction

Composite materials are made up of two main constituents or phases, i.e., reinforcement and matrix phases. Generally, the reinforcement phase, which is stronger and stiff, imparts the strength and stiffness properties of the composite materials, while the matrix phase, which is weaker and soft, binds the reinforcing fibers, transfers loads between fibers, and makes the net shape of the composite. The reinforcing component of a composite can be in the form of short or continuous fibers, particles, or whiskers [1]. Based on the application and importance of composite materials, different materials of reinforcement are available on the market depending on the desired performance and cost of the resultant composite materials. Hence, developing the reinforcing fiber materials design and processing to reduce the cost of manufacturing with acceptable material properties can attract the interest of industrial owners to deliver more reliable products to the market.

The aim of fabricating composite materials is to produce lightweight structures with higher mechanical properties and performance in comparison to conventional materials such as metals. A composite material generally presents superior properties to its ingredients utilized individually. Structural composites aim to optimize the performance of the structure during the service life. Various materials can be employed for the matrix phase such as polymers, ceramics, metals, etc. However, polymeric materials, due to their easy processing, low cost of production, and high productivity are the favorite material for the matrix phase of composites. Ceramics and metal matrices are usually utilized in very high-temperature environments such as engines. Typical polymers used as the matrix material are epoxy, phenolic, and polyester resins. The most commonly used reinforcing materials in composites are carbon, graphite, Kevlar, and glass, which can be dispersed in the matrix in various forms. Carbon fiber-reinforced polymeric composites deliver a composite material with higher performance and lower weight than other fiber-reinforced composites with a higher cost of production. Recently, polymeric composites reinforced with nanofibers have attracted the attention of many researchers, but the cost of nanomaterials is high, and this is the main obstacle to producing nanocomposites on commercial scales [2]. However, additive manufacturing technology can be a cost-effective approach to fabricating fiber-reinforced composites [3].

Fiber-reinforced polymer composites are widely used in many industrial applications from high-performance structural applications such as ships, spacecraft, aircraft, buildings, bridges, off-shore platforms, etc. to low-performance structural applications such as boats, automotive parts, sports goods, etc. [4–7]. The demands for fiber-reinforced polymer composites are increasing due to their outstanding properties compared with conventional materials, and they are capturing other markets such as biomedical devices, energy storage devices, microelectronic devices, etc. as examples of functional applications. Carbon fibers are commonly used as the reinforcing material in the fabrication of advanced composite materials for both structural and functional applications due to their lower weight, high stiffness, high strength, and high fatigue resistance. Other commercially available reinforcing fibers such as Kevlar, boron, and glass are typically utilized in various structural and functional applications in which high strength and performance are not required.

Although carbon fibers have more advantages than other fibers, their high cost of production is a barrier for commercial production purposes. Hence, developing the process of carbon fibers production through deriving from inexpensive natural resources can decrease their production cost to be comparable with other low-cost fibers such as glass at least for functional and structural applications when lower strength is needed. Accordingly, the main objective of this paper is to review and discuss the process of carbon fiber production from common precursors and then introduce a cost-effective process for carbon fiber production from low-cost petroleum asphaltene with the corresponding challenges.

This paper mainly reviews commercially available fibers and their applications and outlook on their markets. In addition, the review briefly discusses the production processes of existing fibers, especially carbon fibers. In addition, both the structural and functional applications of carbon fibers are reviewed and discussed, and then, the carbon fiber production from petroleum asphaltene is introduced and investigated. Lastly, we discuss a market assessment of asphaltene-derived carbon fibers and their advantages over other commercially available fibers as well as challenges in commercializing the asphaltene-based carbon fibers.

2. Existing Reinforcing Fibers

There is a large variety of reinforcing fibers for composites. The favorite properties of reinforcing fibers are their high stiffness, high strength, and relatively low density, where these characteristics can be chosen based on the application of a composite material as well as its fabrication cost. Each type of reinforcing fiber has its advantages and disadvantages, as presented in Table 1 [1]. Most fibers display a linear behavior to failure. The ultimate strain of fibers affects greatly the strength of the composite laminate. High specific stiffness (modulus to density ratio) and high specific strength (strength to density ratio) lead to high-performance composites. These two properties strongly depend on the fibers [1]. In the following, some commercially available fibers in the market are introduced.

Table 1. Advantages and disadvantages of reinforcing fibers (adapted with permission from Ref. [1]).

Fiber	Advantages	Disadvantages
E-glass, S-glass	High strength Low cost	Low stiffness Short fatigue life High-temperature sensitivity
Aramid (Kevlar)	High tensile strength Low density	Low compressive strength High moisture absorption
Boron	High stiffness High compressive strength	High cost
Carbon (AS4, T300, IM7)	High strength High stiffness	Moderately high cost
Graphite (GY-70, Pitch)	Very high stiffness	Low strength High cost
Ceramic (Silicon, Carbide, Alumina)	High stiffness High use temperature	Low strength High cost

2.1. Carbon Fibers

Carbon fibers are widely used in the fabrication of advanced composites with different forms and ranges of stiffness and strength. The mechanical properties of carbon fibers are strongly dependent on how they are treated and manufactured by the organic precursor and processing conditions used [1]. The diameter of carbon fibers is about 5 to 10 µm (0.00020–0.00039 in), and they are composed mostly of carbon atoms (92 wt%). The main advantages of carbon fibers are their high tensile strength, high stiffness, low weight-to-strength ratio, high-temperature tolerance, low thermal expansion, and high chemical resistance, which have made carbon fibers the most widely used and very popular reinforcing fiber in various industries such as aerospace, civil, and motorsports. However, they are costly and expensive in comparison to similar fibers, such as basalt fibers, glass fiber, or plastic fibers [8]. In terms of the overall application, the association of composite companies and research institutes, Carbon Composites e.V. (CCeV), reported that defense and aerospace were the largest consumers of carbon fiber followed by sports/leisure sectors and wind turbines in the year 2013, as displayed in Figure 1 [9]. Due to the extraordinary properties of carbon fibers, they can be ideal reinforcing and matrix phases for composite materials requiring high specific strength (strength/weight ratio). As a carbon fiber, it may be dispersed in polymer matrices to deliver carbon/polymer composites and/or embedded in a carbonaceous matrix to construct carbon/carbon composites. Carbon fibers, either in form of unwoven or woven into fabric sheets, have been widely used in many applications such as aerospace, marine, and automotive industries [1].

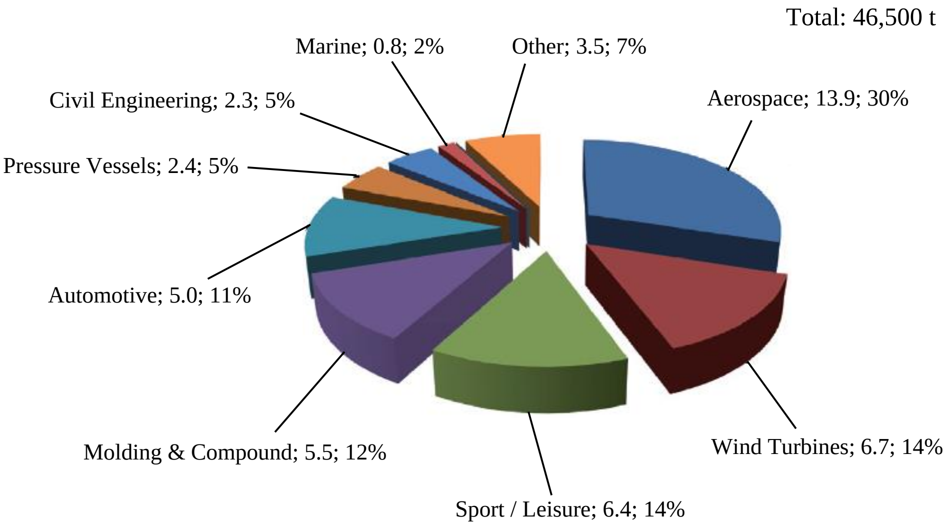


Figure 1. Carbon fiber global demand in the year 2013 (adapted with permission from Ref. [10]).

2.2. Glass Fibers

Glass fibers are commonly used in the fabrication of composites with low to medium performance because of their high tensile strength and low cost. However, they are not recommended to be utilized in composites with high performance due to their relatively low fatigue endurance, low stiffness, and rapid property degradation. Glass fibers are fabricated by the extrusion of a molten mixture of silica (SiO_2) and other oxides through small holes of a platinum bushing. Glass fiber diameters are in the range of 10–20 μm (0.4×10^{-3}–0.8×10^{-3} in). Glass fibers are amorphous and considered isotropic [1].

2.3. Kevlar (or Aramid) Fibers

Kevlar (or Aramid) fibers are organic fibers produced by dissolving the polymer (aromatic polyamide) in sulfuric acid and extruding it through small holes in a rotating device. Kevlar fiber diameter for composite application is typically 12 μm (0.5×10^{-3} in). Kevlar fibers deliver higher stiffness than glass fibers with low density (about half that of glass), excellent toughness, high tensile strength, and impact resistance, but they deliver very low transverse tensile strength and longitudinal compressive strength. They are very anisotropic mechanically and thermally due to their high molecular orientation [1].

2.4. Ceramic Fibers

Boron and other ceramic fibers, such as alumina (Al_2O_3) and silicon carbide (SiC), have high use temperature, high stiffness, and reasonably high strength. Ceramic fibers are not commonly blended or dispersed in polymeric matrices but are used with ceramic or metal matrices for high-temperature applications. Boron fiber-reinforced composites have limited usage for local stiffening and repair patching due to their high stiffness [1].

3. Carbon Fiber Processing from Precursors

To produce carbon fibers, a precursor is needed, and the choice of a precursor can be influenced by a variety of factors such as availability, cost, renewability, inorganic content, ease activation, and carbon yield. In the following, carbon fiber production from precursors is demonstrated.

3.1. PAN-Based Carbon Fibers

Polyacrylonitrile (PAN) is a synthetic and semicrystalline organic polymer resin. PAN is the most commonly used precursor for carbon fiber production and theoretically yields 68% carbon and delivers carbon fibers with a high elastic modulus (344 GPa) and high tensile strength (2070 MPa). PAN-based carbon fibers are stretched initially from 500% to 1300% and then thermostabilized in an oxygen atmosphere between 200 and 300 °C under tension. Afterward, fiber is carbonized (heat treatment under an inert atmosphere between 1000 and 1700 °C); then, the graphitization is conducted (heat treatment between 2500 and 3000 °C), and finally, through surface treatment and epoxy sizing, carbon fibers will be ready for use (Figure 2). Currently, PAN-based carbon fibers, due to their higher strength and moderate elastic modulus, occupied 90% of the carbon fiber market, and the remaining market is supported by carbon fibers derived from other precursors [11–13]. However, the main disadvantage of PAN-based carbon fibers is their high cost of processing.

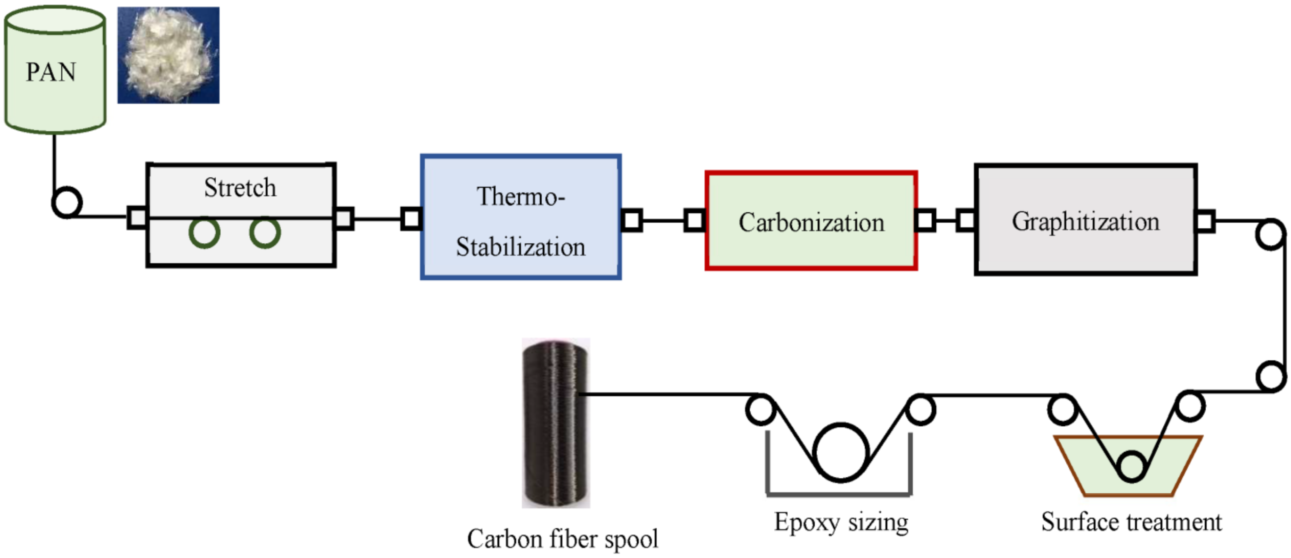


Figure 2. Carbon fiber production using PAN precursor.

3.2. Pitch-Based Carbon Fibers

Petroleum pitch, as a viscoelastic polymer, is another common precursor used for carbon fiber production. Both isotropic and mesophase pitches are utilized for the production of carbon fibers. The theoretical carbon yield of pitch precursors is 80%. Pitch-based carbon fibers are also produced with the same processes used for PAN-based fibers production without an expensive stretching process during heat treatment to have aligned crystallites (Figure 3) [14]. Pitch-based carbon fibers lead to lower tensile strength and higher elastic modulus (about 1050 GPa) than PAN-based carbon fibers [15–18]. Moreover, pitch-based carbon fibers present better thermal and electrical properties than carbon fibers produced by PAN precursors [11]. However, internal voids, surface defects, and other contaminations in the pitch structure lead to a decrease in the mechanical properties of produced carbon fibers [19].

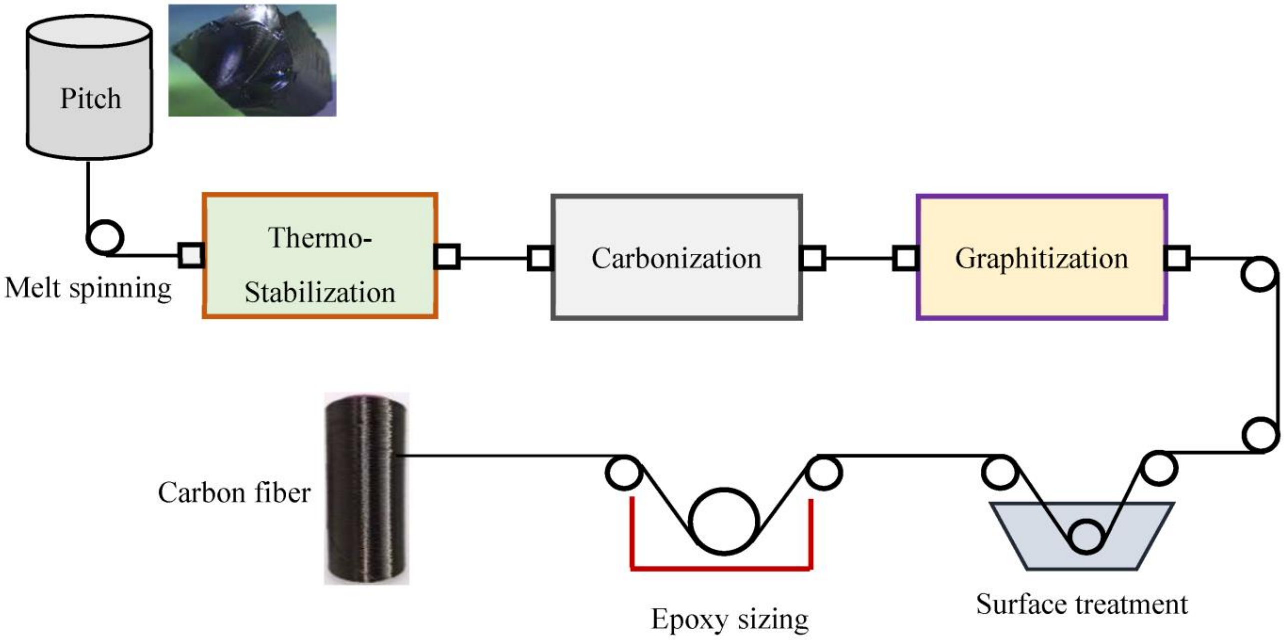


Figure 3. Carbon fiber production using petroleum pitch precursor.

3.3. Lignin-Based Carbon Fibers

Lignin is an organic polymer forming key structural materials in the tissues of most plants. Lignins are polymers made by cross-linking phenolic precursors [20]. Lignin contains a high carbon percentage (60–65%), which leads to high carbon yield after fiber processing, hence making it an alternative to PAN precursor for carbon fiber production. Lignin-based carbon fibers are produced by the melt spinning under an inert atmosphere. The lignin fiber is then oxidatively thermostabilized and carbonized and finally graphitized with the surface treatment (Figure 4).

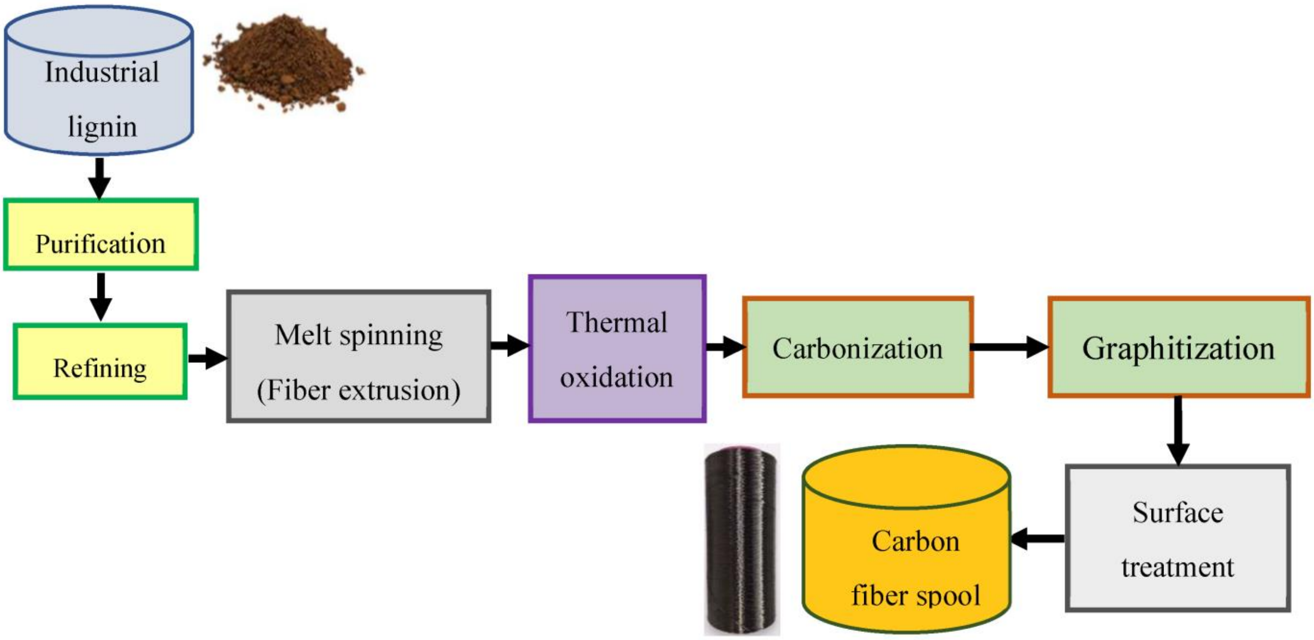


Figure 4. Process of fiber production from industrial lignin.

The mechanical properties of lignin-based carbon fibers are not high enough to meet some criteria for structural applications such as the requirement set by the US automotive industry [21]. It is found that the lignin-based carbon fibers presented a tensile strength of 388–1060 MPa and elastic modulus of 40 GPa [22,23]; however, they exhibited a weak blending with the polymer matrices [24,25].

In addition, the long stabilization time (over 100 h) [26] is problematic as well as the challenges in the melt spinning of kraft lignin without plasticizing additives [22,27]. The process of obtaining high-strength carbon fiber from the lignin is complex and needs careful control of melt spinning conditions, ramping profiles, and treatment temperatures. The lignin should have a low enough melt flow temperature to be melt spun without polymerizing during extrusion, but a high enough glass transition temperature for fiber stabilization is required to proceed at an acceptable rate. Although lignin has some limitations and does not lead to high-strength carbon fibers obtained from other precursors (PAN and pitch), it is renewable, very inexpensive, and is already oxidized, leading to being oxidatively thermostabilized at higher rates than either PAN or pitch [21].

3.4. Cellulose-Based Carbon Fibers

Cellulose, the most abundant organic polymer on earth, is abundantly found in the primary cell wall of green plants, the oomycetes, and many forms of algae. Overall, 90% of cotton fiber content, 40–50% of wood content, and approximately 57% of dried hemp content is cellulose [28]. Cellulose-based carbon fibers can be extracted from cotton, wood, hemp, flax, sisal, rayon, and linen. However, among them, rayon has been utilized commercially and extensively studied. The molecular orientation of cellulose, in contrast to lignin, significantly influences the mechanical properties of carbon fibers [29].

Similar to the process of PAN- and pitch-based carbon fibers, thermal oxidation/stabilization, carbonization, and an optional graphitization as well as the surface treatment are utilized to convert cellulose (from plants) to carbon fibers [30]. Heating the fiber at $T > 400$ °C leads to cellulose pyrolyzing and then by heating to $T > 1000$ °C, the carbonization is completed. Finally, the fiber is graphitized by heating at $T > 2000$ °C with 100% carbon for all practical applications. Cellulose-based carbon fibers have a low elastic modulus; for example, rayon-based carbon fibers have a low elastic modulus of 27.6 GPa. To obtain high-modulus carbon fibers from cellulose precursors such as rayon, carbon fibers should be stretched at the final heat treatment temperature, which is a costly process [14].

The production of cellulose-based carbon fibers is mainly inhibited due to the low carbon content of cellulose (44.4%) and delivering low-yield carbon fibers (10–30% after carbonization) because of releasing carbon-containing gases such as CO and CO_2 in the process [30]. A comparison of material properties of carbon fibers produced using different precursors is shown in Table 2 [31].

Table 2. Properties of carbon fibers from different precursors (Adapted with permission from Ref. [31]).

Carbon Fiber	Diameter (µm)	Density (g/cm^3)	Elastic Modulus (GPa)	Tensile Strength (MPa)	Elongation at Break (%)
PAN-based carbon fiber	5–10	1.7–1.8	200–500	3500–6300	0.8–2.2
Pitch-based carbon fiber	10–11	1.8–2.2	150–900	1300–3100	0.3–0.9
Lignin-based carbon fibers	—	—	40	388–1060	—
Rayon-based carbon fiber	5–10	1.4–1.5	40–100	500–1200	—
Lyocell-based carbon fiber	8	—	90–100	900–1100	1–1.1

4. Applications of Carbon Fibers

After the end of classic wars in the world and changes in the political situation, the usage of carbon fibers in military industries has decreased because of a major cut in defense. Hence, commercial applications of carbon fibers have grown extensively in many industries. Due to rapid development and advance in the composite field, some applications of carbon fibers may now have been discontinued and replaced with new applications in new technologies. Figure 5 portrays, briefly, various applications of carbon fibers. In the following, functional and structural applications of carbon fibers are explained in detail with some practical examples.

4.1. Functional Applications of Carbon Fibers

Carbon fibers are widely used as a functional material with applications in various industries as explained in the following.

4.1.1. Molecular Sieves

Molecular sieves are materials with uniform size pores or very small holes. These pore diameters are similar in size to small molecules, and thus, large molecules cannot enter or be adsorbed, while smaller molecules can [32]. Figure 6 shows a carbon molecular sieve. Molecular sieves produced from carbon fiber composites are able to absorb CO_2 emitted from gas turbines and coal-fired power plants. To produce this product capable of absorbing CO_2, a pitch-based chopped fiber-reinforced phenolic resin composite is activated in steam, O_2, or CO_2 at 850 °C. The molecular sieve has a pore volume with mesopores of 2–50 nm and a large surface area. It also has macropores (50–100 mm) allowing sufficient fluid flow with low-pressure drop. The molecular sieve can also be used for the removal of CO_2 from fuel cells or natural gases [33].

Figure 5. Various applications of carbon fibers.

4.1.2. Catalysts

Carbon fibers have the potential to be used as catalyst support by making a porous carbon fiber carbon composite with a density of 40.2 g/cm^3, a significant volume of mesopores (2–50 nm), and macropores (50–100 mm) allowing excellent fluid flow with minimal pressure drop. The procedure to reach this product include: slurring Fortafil P200 PAN-based carbon fiber in water with a phenolic resin, vacuum molding, drying at 50 °C, curing for 3 h at 130 °C and carbonization in a flow of N_2 at 650 °C [33–35].

4.1.3. Electrical Conduction

The early application of PAN-based carbon fiber, when it was developed in the 1960–1970 era, was in wall panels to prevent heat loss and keep the room warm. Nowadays, with the advances in technology, the PAN-based woven carbon fiber can be used as a large area temperature sensor, a portable heating unit, a flexible heating element, an electrical switching function, a warning and control device, and a temperature management system [36].

Figure 6. Carbon molecular sieve (reprinted with permission from Ref. [37]).

4.1.4. Electrodes

Carbon fibers are used in the fabrication of electrodes. For example, carbon fiber microelectrodes are utilized to extracellularly record neuronal action potentials [38] and to detect electrochemical signals in vivo and in vitro [39]. Furthermore, they have been used for the detection of catecholamines such as norepinephrine or dopamine and other oxidizable biological species such as nitric oxide [40]. Carbon fiber microelectrodes can be used in sensing tissue oxygen levels at a micrometer scale. In another application, the immobilization of DNA molecules or carbon nanotubes onto carbon fiber microelectrodes leads to making microsensors for various analytes [41].

The carbon fiber microelectrodes are graphite monofilaments with a 7 μm diameter. To construct carbon fiber microelectrodes, carbon filaments are placed in a mechanically supportive and electrically insulating borosilicate glass tube or plastic sheathing and an uninsulated carbon tip protruded from the sheathing by 10 μm to a few 100 μm (Figure 7). The carbon tip creates an electroactive surface for picking up spikes from the near vicinity neurons and/or surface for electron transfer in micro-biosensors applications and electrochemical measurements [41].

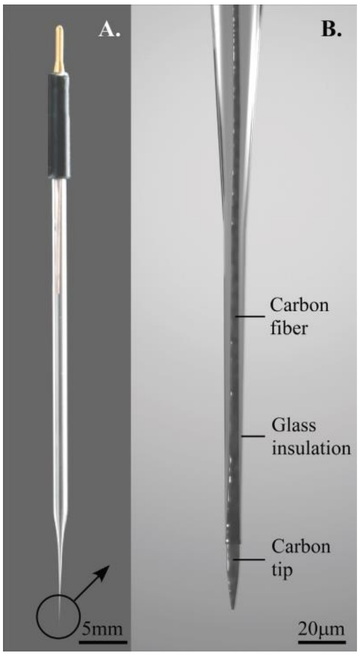


Figure 7. (**A**) View of a carbon fiber microelectrode, and (**B**) microstructure of the tip (reprinted with permission from Ref. [41]).

4.1.5. Energy Storage Devices

Electrochemical energy storage devices, such as fuel cells, batteries, and electrochemical capacitors, act as portable or stationary stores of electric power for later use and thereby are crucial for expanding the contribution of sustainable and renewable energy resources. Carbon fibers, due to their exceptional properties, can be used in the construction of electrodes for energy storage devices.

Rechargeable lithium-ion batteries (LIBs), due to their lightweight, high energy density, long lifespan, and environmentally friendly nature, have been widely used in portable electronics, communication devices, transportation, hybrid electric vehicles, and grid-scale applications. However, with the rapid development of electric vehicles and consumer electronics as well as the increasing demand for clean energy, more advanced LIBs with longer life, higher capacity and performance, enhanced charging speed, and improved safety are urgently required. Amorphous carbon fiber, with a proper heat treatment, has a high discharging capacity for the anode material of LIBs. Pitch-based carbon fiber has been utilized for anodes of rechargeable LIBs [42,43]. Figure 8 displays a typical Li-ion cell using a Li_2O cathode and a carbon compound anode which is separated by a microporous membrane, utilizing a non-aqueous electrolyte such as a Li salt dispersed in a mixture of alkyl carbonates [36]. LIBs generate DC power by using chemical reactions. When batteries are charged and discharged, lithium ions move back and forth between the electrodes (anode and cathode). Generally, the cathode material is made of cobalt-, nickel- or manganese-based transition metal oxides, and the anode material is made of graphite. Both the anode and cathode are fabricated using a stacked structure, and the lithium ions are placed between layers. Within charging, the lithium ions move from the cathode to the anode, while within discharging, the lithium ions move from the anode to the cathode (Figure 8) [44].

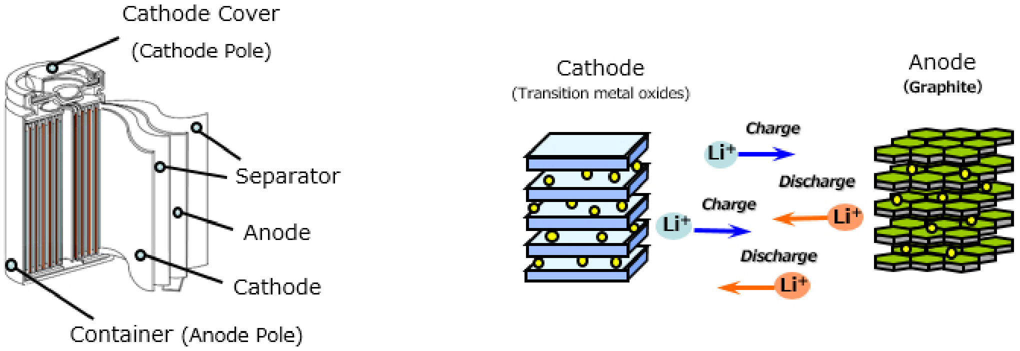


Figure 8. A rechargeable LIB with its components and function during charging and recharging (reprinted with permission from Ref. [44]).

The polymer electrolyte membrane fuel cell (PEMFC) can be a good candidate as a power source for future passenger vehicles due to its high-power density at a relatively low operating temperature of about 80 °C. Figure 9 depicts a layered PEMFC made of various components including end plates, bipolar plates, the gas diffusion layer (GDL), and the membrane electrode assembly (MEA). The bipolar plate is the main component of the PEMFC stack, and its development has a significant effect on the performance of the PEMFC. Hence, a carbon fiber composite can be utilized to develop the bipolar plate of the PEMFC due to the high thermal and electrical conductivities of carbon/epoxy composite as well as its high specific stiffness and strength [45].

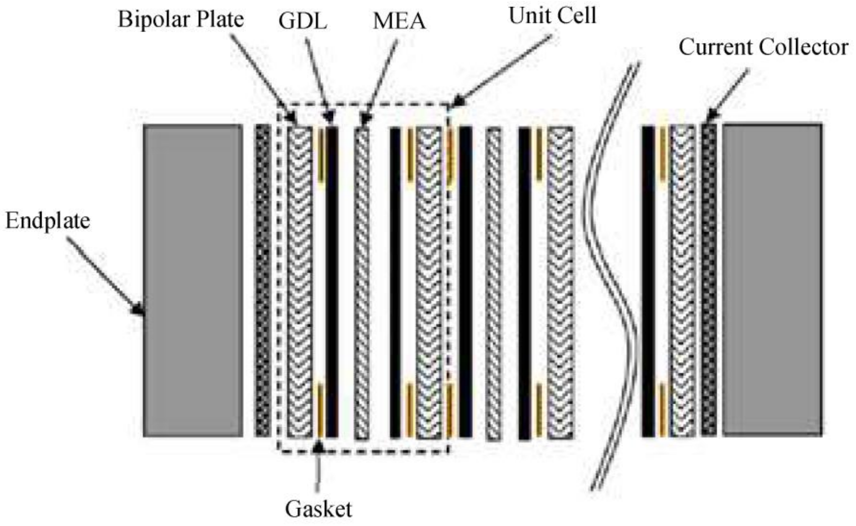


Figure 9. Schematic view of the PEMFC (adapted with permission from Ref. [45]).

Fiber-shaped supercapacitors due to their higher performance are promising energy storage devices for future portable electronic devices. A fiber-shaped asymmetric supercapacitor (ASC) device is composed of metal oxides and directly grown on a flexible and conductive carbon fiber substrate which makes a large work function difference. Specifically, carbon fiber/MoO_3 (CF/MoO_3) and carbon fiber/MnO_2 (CF/MnO_2) are produced using a simple electrodeposition approach. The solid fiber-shaped ASC device is then assembled with CF/MoO_3 as the negative electrode and CF/MnO_2 as the positive electrode. The high work function difference between the high conductivity of the carbon fiber substrate and the metal oxides leads to the ASC device with notable performance. Figure 10 illustrates the overall procedure to assemble the ASC device based on CF/MoO_3 as the negative electrode and CF/MnO_2 as the positive electrode [46].

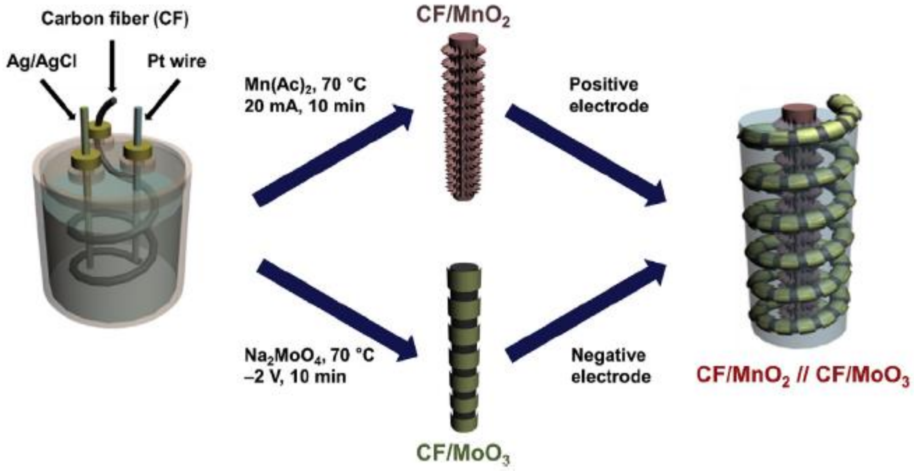


Figure 10. A schematic assembly of a fiber-shaped asymmetric supercapacitor (ASC) device based on CF/MnO_2 as the positive electrode and CF/MoO_3 as the negative electrode, respectively (reprinted with permission from Ref. [46]).

4.1.6. Insulation

Carbon fibers are fire resistant and present high thermal insulation with low electrical conductivity and low smoke emission as well as weight saving. Current applications of carbon fibers as an insulator are in aircraft fire blockers, aircraft fuselage thermal insulation, personal insulation, fire protective clothing, and fire-retardant insulation boards for special lightweight applications. Carbon fibers provide a measure of sound insulation in an aircraft.

They can also be used in packing materials and gaskets, since they have higher thermal and oxidative stability [36]. They can also be used as electromagnetic interface shields in cement matrices for building purposes [47].

4.2. Structural Applications of Carbon Fibers

Using high-strength carbon fiber-reinforced composites for structural applications is economical by reducing the weight of final structures. Hence, carbon fibers in thermoset matrices can be used in many structural applications as described in the following.

4.2.1. Aerospace

Carbon fibers are widely used in the fabrication of aircraft components. Airbus Industries was the first civil aircraft manufacturer in the world that used carbon fiber-reinforced prepreg (CFRP) for the fabrication of parts of the primary structures of the Airbus A300. For example, in the Airbus 350 XWB, 53% of the used materials are CFRP including the wings, center wing box and keel beam, skin panels, tail cone, frames, doors, stringers and doublers (Figure 11) [48]. In 1990, CFRP was also adopted by Boeing as the primary airframe structure material. Overall, 50% of the total weight of the Boeing 787, including the frame and wings, was made of CFRP. Figure 12 displays a comparison between the Boeing 787 and Boeing 767 with aluminum as the main material (77% of the weight) [49].

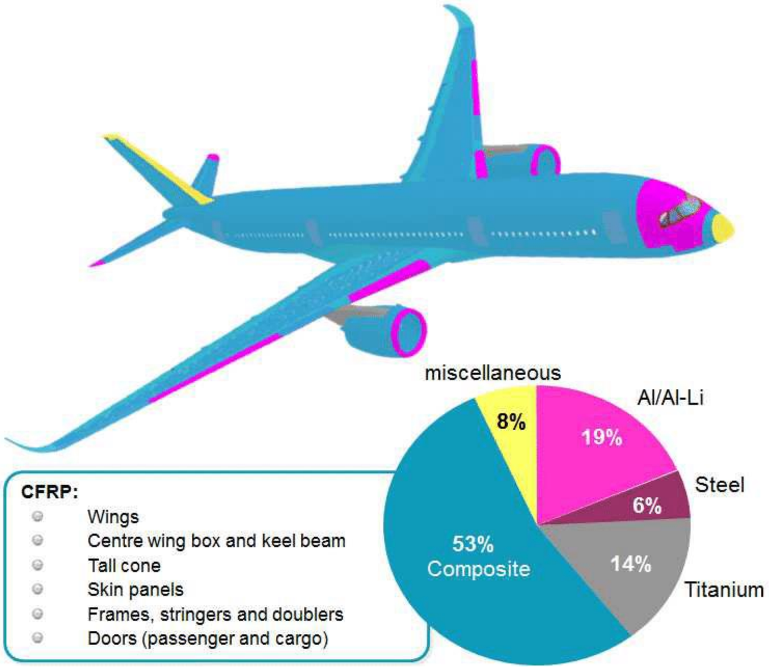
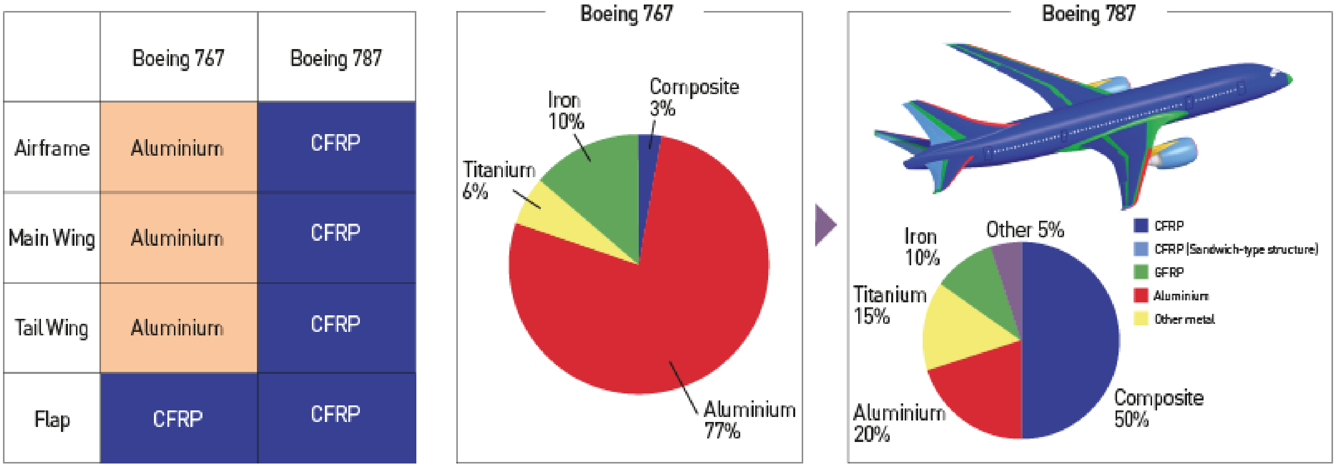


Figure 11. Materials used in the Airbus 350 XWB (reprinted with permission from Ref. [48]).



	Boeing 767	Boeing 787
Airframe	Aluminium	CFRP
Main Wing	Aluminium	CFRP
Tail Wing	Aluminium	CFRP
Flap	CFRP	CFRP

Figure 12. A comparison between the Boeing 767 and the Boeing 787 in using CFRP (reprinted with permission from Ref. [49]).

In past decades, composites have been used in space applications, and due to their outstanding material properties, their use is growing. Composite materials are used in components of human spaceflight vehicles, payloads, satellites, and launch vehicles used to throw these into space. Pressure vessels for fuel and gas storage and solid rocket motors are made of composite materials. Carbon fiber laminates are extensively utilized on satellites and payload support structures. Special high-strength carbon composites are used for the hottest components in rocket nozzles such as exit cones and throat. Carbon–carbon panels are utilized on the wing leading edge and the nose of space shuttles to protect them from high temperatures exceeding 2300 °F experienced during re-entry. Carbon fiber-reinforced phenolic is used to make ablative composites to absorb heat by changing states. The ablative heat shield was utilized in Apollo and Orion capsules, which will return humans to the moon and beyond [50]. Typical structural components of a space vehicle fabricated from CFRP are displayed in Figure 13 [51]. Furthermore, carbon fiber-reinforced composites are commonly utilized in aero engines, propeller blades, and Unmanned Aerial Vehicles (UAVs).

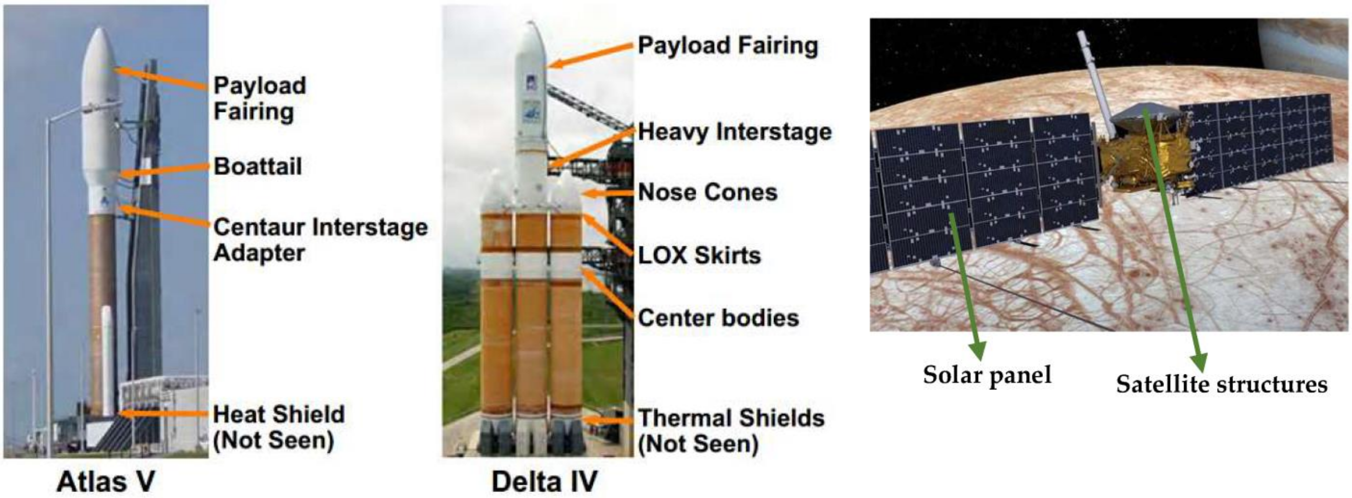


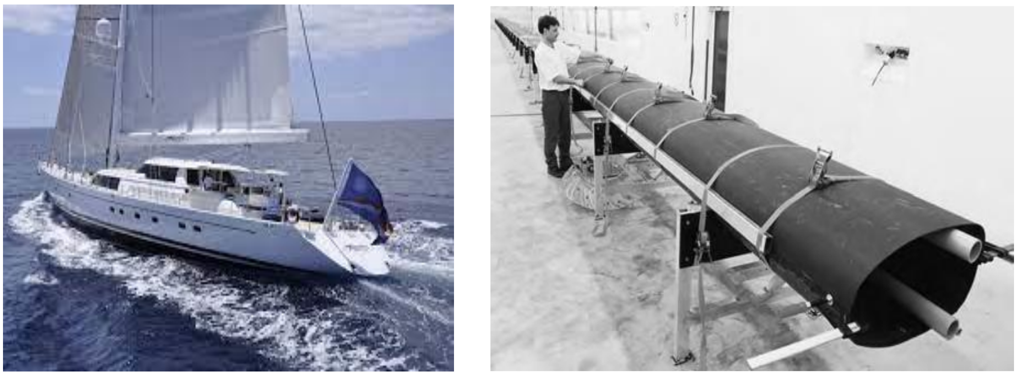
Figure 13. Schematic space vehicle (adapted with permission from Refs. [51,52]).

4.2.2. Marine

Sport boats are made of CFRP with a honeycomb core based on the dry prepreg approaches. A carbon fiber-reinforced composite racing catamaran (Team Philips) (Figure 14) made by Goss Challenges is one of the largest carbon composite structures fabricated in Europe (36.5 m long and 21 m wide, with an unstayed mast of 39 m high) [53].

Figure 14. A Team Philips catamaran (reprinted with permission from Ref. [54]).

In another example, the hull and beams of the 38 m long catamaran PlayStation were built from CFRP/AL honeycomb, and its mast was made of carbon fiber, which was 45 m above the water. This catamaran led to a new world record for boating from Miami to New York. The Consolidated Yacht company fabricated a tall mast (53.33 m) with two halves for the yacht from the carbon/epoxy prepreg. Generally, tall masts are built in several sections because of limitations of the curing oven, but a 59 m long mast made of carbon fiber prepreg was fabricated in one piece for the yacht Hyperion (Figure 15) [36].



(**a**) (**b**)

Figure 15. (**a**) Hyperion 2 yacht and (**b**) Hyperion 2 yacht mast with 59 m length fabricated from CFRP (adapted with permission from Refs. [36,55]).

4.2.3. Automotive

Recently, carbon fiber-reinforced composites have been used to fabricate automotive parts. It was reported that a bonnet fabricated from carbon fiber-reinforced composites can decrease its weight from 18 to 7.25 kg. In another example, carbon fiber was used in fabricating the hood of GM's Corvette to reduce its weight to 9.3 kg, saving 4.8 kg from the standard fiberglass SMC [56]. Furthermore, carbon fiber-reinforced composites can be used in the fabrication of the chassis, the body, and the interior of cars, where many automaker companies have used it in their products [36]. Carbon–carbon is also utilized in the fabrication of brakes and clutches. Suspension systems of cars also benefit from carbon fiber composites: for instance, BMW uses carbon fiber in the BMW Z22 model to reinforce the roof, tailgate, flooring, and side frames, which leads to 20 parts replacing 80 components with 50% less weight than a steel body [36]. CFRP can also be utilized to fabricate pushrods with 70% less weight than metal pushrods and decreasing noise and increasing engine efficiency [57].

Carbon fibers have been used in the fabrication of drive shafts for many years with more advantages than metallic drive shafts including less weight, improved mechanical properties, excellent torsional strength, good corrosion resistance, improved damping characteristics, high fatigue resistance and torsional compliance reducing shock loads on gears and universal joints. It was reported that the weight savings of pure aluminum, Al/carbon/epoxy composite, E-glass/epoxy composite, Kevlar/epoxy composite, and carbon/epoxy composite drive shafts were obtained, respectively, 46.157%, 53.865%, 36.87%, 64.615%, and 69.236% of the weight of the conventional steel drive shaft, where the carbon fiber-reinforced composite provides high strength and lighter components meeting the design requirements [58]. Initially, the cost of carbon fiber-reinforced composite drive shafts was a significant concern and drawback for industrial sectors to produce on commercial scales, and with the development of fibers and reduction in the fabrication cost, thousands of composite shafts are in service now in the industry today. Heavy goods vehicles and buses are also beneficial in using carbon fibers in their components. For example, CFRP leaf springs are 80% lighter than steel springs with the same spring rate and load-carrying capacity. A hybrid of carbon and glass bumper is used in buses and heavy trucks with higher corrosion resistance, superior vibration resistance, and much less weight than metallic ones [36]. Figure 16 describes briefly automotive parts which can be replaced with composite materials.

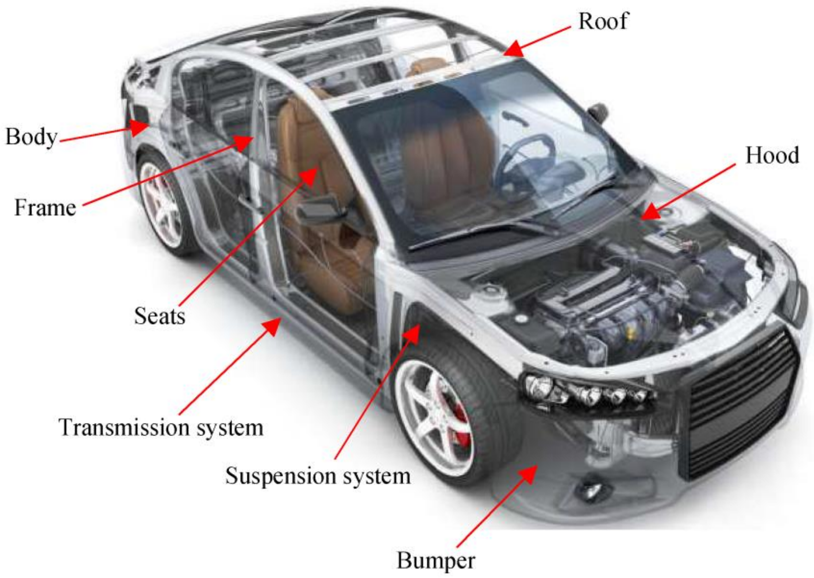


Figure 16. Automotive parts can be replaced with composites (adapted with permission from Ref. [59]).

4.2.4. Oil and Gas Extraction and Transmission Pipelines

The oil industry is now interested to extract oil from deep water at a depth of more than 1 km in areas such as the Gulf of Mexico, the Gulf of Guinea, the Caspian Sea, and Brazil. In the Brazil location, Petrobras/RB Falcon could reach a depth of 2777 m, and obviously, the risk factor increases with the depth increase, where the oil companies will need smart systems composed of composite structures. In offshore oil drilling installations, carbon fiber-reinforced composites can be used in drilling risers, as shown in Figure 17 [1].

At deep water, CFRP risers, rig, and tendons components lead to lower costs and offer considerable savings over conventional materials. The standard platform installation is not suitable, and its modification is extremely costly. In water deeper than 1600 m, a tension leg platform, based on carbon fiber composite cables as tethers, leads to lower costs. Spencer composites through over-winding carbon fiber and fiberglass onto Ti tubing fabricates drilling rise about 15 m long and 560 mm diameter, weighing 20% less, costing 40% less, and with an extended fatigue life [36].

Figure 17. Composite drilling riser for offshore oil drilling: 15 m long, 59 cm inside diameter, 315 bar pressure; manufactured for Norske Conoco A/S and other oil companies (reprinted with permission from Ref. [1]).

There are high lengths of oil and gas pipelines in the world, and most of the highest ones are in North American countries. Including these pipelines, it is estimated that 60% of the world's oil and gas transmission pipelines have been used for more than 40 years and are at risk of defects. External corrosion, internal corrosion, erosion, abrasion, dents and cracks are typical defects that may occur in oil and gas transmission pipelines and potentially lead to disasters and catastrophic incidents. If we do not monitor and repair these pipelines, these defects could make expensive and potentially deadly outcomes to the operators and owners of the pipelines as well as disasters to civilians. Therefore, to prevent further disasters and damages to other intact sections of the pipelines, an urgent repair or replacement of defects at the damaged locations is required, depending on the severity of the defects. Advanced composite wraps have been widely used within oil and gas transmission pipelines over the past two decades for the permanent repair and reinforcement of sections of the pipe wall, which have been weakened due to the defects such as corrosion, cracks, etc. (Figure 18a) [60]. Unidirectional carbon fiber-reinforced composite can be used to fabricate composite wraps or sleeves with high strength to withstand high pressure applied by ongoing oil or gas (Figure 18b). The composite wrap exceeds the yield strength of the original pipe and delivers a more economical repair solution than other approaches [61].

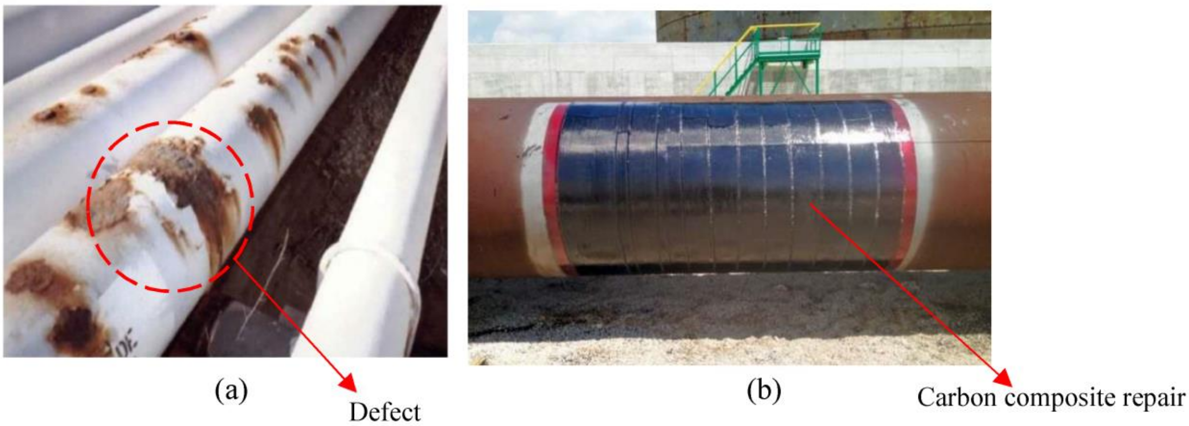


Figure 18. (**a**) Typical defects on transmission pipelines [60], and (**b**) carbon fiber-reinforced composite wraps to repair defected sections of pipelines [61] (adapted with permission from Refs. [60,61]).

4.2.5. Biomedical Devices and Sport Goods

Carbon fibers have been used in biomedical applications such as prosthetic devices, artificial limb parts, and implants (Figure 19). Furthermore, CFRP has been used in leisure and sports products such as golf clubs, skis, fishing poles, tennis rackets, and bicycles. An example of a carbon fiber-reinforced composite bicycle frame is displayed in Figure 20. For instance, the Applied Composite Technology company fabricates artificial feet from carbon fiber epoxy prepreg with high efficiency for athletes where it was reported that a sports event participant with an artificial foot ran 100 m in 11.3 s in the 1996 Atlanta Paralympic Games. In another example, Ossur, an Icelandic company, used braided carbon fiber to fabricate a custom-made socket for a limb amputee with a high rate of conformity. Carbon fibers have been widely used in dental restorations, implants and prostheses as well as other medical devices [36].


(**a**) (**b**) (**c**) (**d**)

Figure 19. (**a**) Carbon composite mechanical hand [62], (**b**) carbon/epoxy composite leg prosthesis, (**c**) carbon/epoxy foot prosthesis, and (**d**) carbon/polysulfone hip prosthesis [1] (adapted with permission from Refs. [1,62]).

Figure 20. Carbon/epoxy composite bicycle frame weighing much less than the corresponding steel frame (reprinted with permission from Ref. [63]).

5. Challenges in Carbon Fibers Production

The main obstacle in the production of carbon fibers is the high cost of precursors which includes more than 50% of the total cost of carbon fiber production [21]. The production of commercial-grade carbon fibers from pitch and PAN precursors is expensive due to the high cost of raw materials and complex processing steps with USD 15–20 per kg for pitch-based carbon fibers and USD 18–35 per kg for PAN-based carbon fibers [64]. Meanwhile, Kevlar and glass fibers cost, respectively, USD 23 and USD 2 per kg. It was also reported that PAN-based carbon fibers cost USD 35 per kg for use in the automotive industry [65]. If the cost of carbon fiber fabrication decreases to USD 11 per kg, carbon fiber-based automotive parts can be cost-competitive with steel-based automotive components with an average cost of USD 5 per kg. By using carbon fiber-reinforced composites in the automotive industry in the fabrication of automobile bodies, engine parts, transmission shafts, interior components, suspension systems, brakes, etc., the automobile manufacturing cost can be driven down by 80% due to a decrease in tooling and simpler manufacturing and assembling procedures as well as reducing the fuel consumption and cost by having a lighter weight automobile than a steel-based one. Using lightweight carbon fibers in batteries of electric vehicles could also be cost-effective by reducing the electricity consumption by cutting the weight of batteries where the lightest produced batteries by Tesla weigh over 450 kg [66].

To use carbon fibers in industrial applications, two essential criteria need to be considered: the cost (price per kilogram) and performance (mechanical/thermal/electrical properties) in comparison to conventionally used materials such as steel, aluminum, etc. The US Department of Energy [67] published the accepted minimum properties of carbon fibers which can be used as a reference in the production of low-cost carbon fibers. Over the past two decades, many research studies have been dedicated to producing low-cost carbon fibers with sufficient mechanical properties from inexpensive resources such as biomass (cellulose and lignin), coal, and petroleum by-products [22,68–70]. One of the natural materials that could be used as a precursor in carbon fiber production is petroleum asphaltene; its potential and applications, as well as carbon fiber processing from asphaltene, will be discussed in the next sections.

6. Asphaltene-Based Carbon Fibers

Asphaltene is a molecular substance found in crude oil, along with resins, aromatic hydrocarbons, and saturates. Asphaltene consists of carbon, hydrogen, nitrogen, oxygen, sulfur, vanadium, and nickel. Heavy oils, oil sands, and bitumen have higher proportions of asphaltene than light oils. Asphaltene can be an ideal candidate to be used as a precursor to producing carbon fibers due to their low cost (USD 0.05 per kg) with abundant resources and high carbon (C) to hydrogen (H) ratio (1:1.2), depending on the asphaltene source [71]. Hence, low-cost and high-performance carbon fibers can be derived from asphaltene precursors for wide usages from functional to structural applications. As described before, carbon fiber production generally consists of several main procedures, i.e., spinning, oxidation/stabilization, carbonization, and graphitization. Stabilization is the slowest and most energy-consuming process affecting both mechanical properties and the cost of carbon fiber production [72–74].

Due to its high carbon content, heteroatom, aromaticity, double bond equivalent (DBE), and polar functional groups, asphaltene potentially can be used for the synthesis and development of functional carbonaceous materials and structures [75,76]. Asphaltene-based carbon fibers could be fabricated through optimization of the process of polymer blend and nano-reinforcement for applications in functional composites (such as energy storage devices, gas adsorbents, water treatment, etc.) and structural composites (such as automotive components, aerospace structures, marine structure, biomedical devices, sports goods, etc.). Producing carbon fibers from inexpensive feedstock such as petroleum asphaltene could reduce the precursor cost by about 90% and cut down the carbon fiber production cost from about USD 18–35 per kg (PAN-based carbon fibers) to less than USD 9 per kg [77].

Pitch (including asphaltene)-based precursors have a lower cost than PAN-based precursors with a higher elastic modulus and extremely lower tensile strength and failure strain than PAN-based carbon fibers. To have a low-cost carbon fiber with acceptable mechanical properties required for various applications, the development of a new carbon fiber precursor through a blend of asphaltene and PAN precursors can enhance fiber spinning, which results in a combination of lower cost, better ductility, and improved modulus and strength without the brittleness observed in the pitch-based carbon fibers. This hybrid (asphaltene/PAN) precursor can be further reinforced with nanofillers, such as carbon nanotubes (CNTs), graphene, and nanocrystal cellulose (NCC) to improve the mechanical properties.

7. Asphaltene-Based Carbon Fiber Processing Steps

The raw asphaltene is provided from natural resources without further purification. Then, the elemental composition is determined, and samples are finely ground before the measurement and weight into crucibles. Green fibers are produced through a melt spinning process where the raw asphaltene is melted at a temperature of 197 °C. It is necessary to prevent fiber from melting during carbonization at high temperatures. Then, an oxidative stabilization process is conducted on asphaltene fibers. It was found that by oxidative stabilization without acid pretreatment, the fibers will not retain their fibrous shape, while with acid pretreatment (OF_{HNO_3}), a visible fibrous shape of asphaltene fibers is obtained (Figure 21) [78].

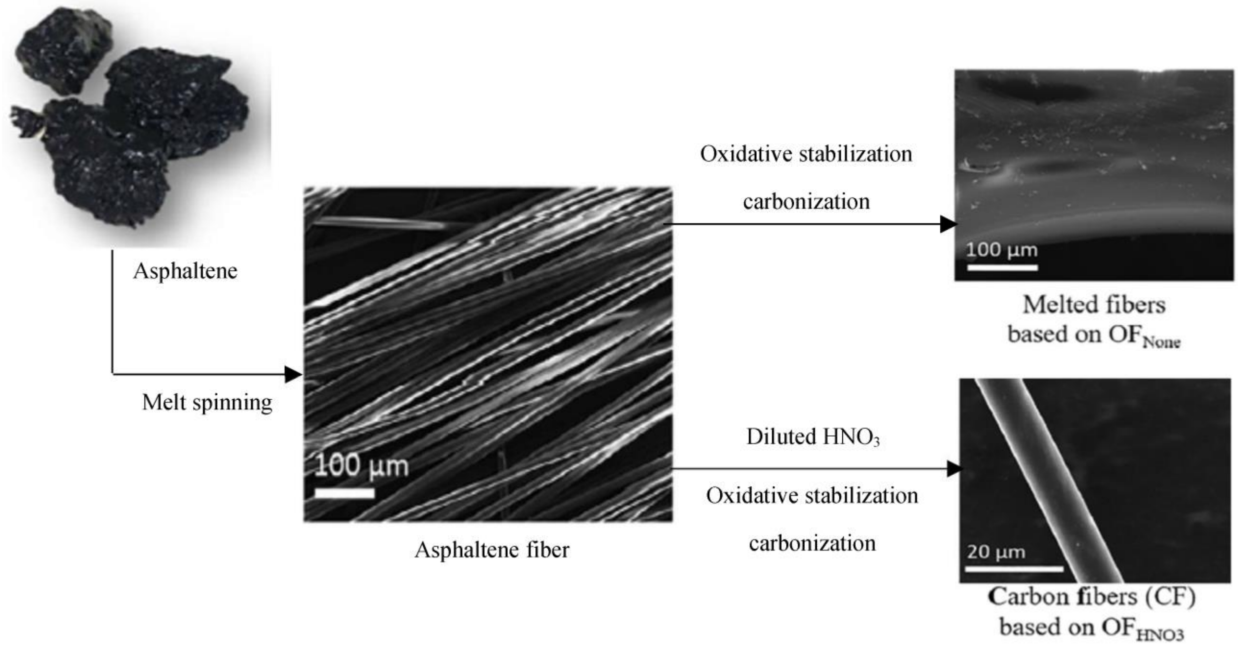


Figure 21. Asphaltene-based carbon fiber manufacturing process (reprinted with permission from Ref. [78]).

8. Main Challenges of Asphaltene-Based Carbon Fibers

Similar to any newly developed fibers, producing asphaltene-based carbon fibers will have some challenges, which should be addressed and solved before commercialization. The main challenges that we may face in producing asphaltene-based carbon fibers are:

- Increasing mechanical properties and enhancing the physical properties for novel applications.
- Meeting productivity requirements for novel applications.
- Purification of asphaltene precursors and the defects mitigation of fiber during the extrusion process.
- The impurities and sulfur content can highly impact the spinnability and mechanical properties of the resulting fibers.

To solve and remove these problems, it is suggested to consider the following solutions:

- Using fractionation process of asphaltene by using solvent (such tetrahydrofuran) to separate impurities/insoluble.
- Applying electrospinning to fabricate nanofibers to reduce the defects.
- Exploring an economical approach for reducing/eliminating these impurities and using greener solvents that can be readily recycled and do not cause any health concerns.

9. Required Performance and Properties of Asphaltene-Based Carbon Fibers

In structural composites, the high specific stiffness (stiffness per unit weight) and high specific strength (strength per unit weight) of the reinforcing fibers lead to a high-performance and lightweight structure. Therefore, it is necessary to develop and optimize asphaltene-based carbon fibers to meet the requirements of structural applications. Moreover, to use asphaltene-based carbon fibers in functional applications such as batteries, supercapacitors, and fuel cells, they should have enough electrical conductivity required for the electrodes of energy storage devices.

In addition to the above technical requirements of carbon fibers, some techno-economical challenges should be overcome. For instance, by reducing the cost of the precursor materials (down to USD 10 per kg) as well as improving their mechanical properties, we can attract the attention of the automotive industry. Asphaltene-based carbon fibers by reducing the density by 30% (1.8 g/cm^3 vs. 2.54 g/cm^3) and elastic (tensile) modulus of 70 GPa can compete favorably in the glass fiber reinforcement market. To compete with other fibrous composites, the cost of carbon fiber production should be reduced where we can achieve this goal through the newly developed asphaltene-based carbon fibers with the lower cost of the precursor and processing. It was also found that an electrical conductivity of 5 S/cm can be sufficient for the electrodes of energy storage devices. Accordingly, if we could, firstly, produce asphaltene-based carbon fibers with composite tensile strength: 50–500 MPa, composite elastic modulus: 50–100 GPa, and composite electrical conductivity: >5 S/cm, we can compete with other low-performance fiber-reinforced composites as well as lowering the processing and fabrication costs.

10. Target Markets of Asphaltene-Based Carbon Fibers

10.1. Functional Composites

10.1.1. Energy Storage Devices

Graphite (as carbon fiber) commercially is used as an anode material of LIBs delivering a limited capacity (372 mAhg^{-1}) [79]. Conventional graphite provides limited storage capacity and ion channels because of its stacked sheets. To remove the limitations of graphite, Zn, Mn, Co or Fe alloyed lithium, and metal oxides (e.g., Fe_2O_3, Co_3O_4, Mn_2O_3 and $ZnMn_2O_4$) with relatively higher capacities can be employed to replace the graphite anode [80]. Although metal oxides as LIB anodes lead to high capacity, their industrial application is hindered by the rapid capacity fading and electrode disintegration during Li^+ insertion and extraction due to their inherent poor electrical conductivity.

To solve these problems, significant research studies have been dedicated to stabilizing metal oxides and reducing their pulverization during cycling by accommodating the volume change. It is found that metal oxide/porous carbon composites are a reliable electrode material with superior electrochemical properties and mechanical stability due to their high electrical conductivity, buffering effect, and low activity of the carbon support [81]. In previous research works, porous carbon as a support has an important role to relax stresses and prevent the pulverization and aggregation of metal oxide nanoparticles. $ZnMn_2O_4$, due to the low oxidation potentials of manganese (1.5 V) and zinc (1.2 V) and its high capacity (784 mAh g^{-1}), has attracted much attention to be used as the electrode material to increase the output voltage of LIBs [81]. Furthermore, the low cost and environmental friendliness of $ZnMn_2O_4$, in comparison to Co or Fe-based oxide, are attractive for both governmental and industrial sectors. The industrial application of $ZnMn_2O_4$/porous carbon as electrodes of LIBs can develop a low-cost and environmentally friendly mechanism for the delivery of $ZnMn_2O_4$/porous carbon for LIBs. Asphaltene-based carbon fiber is a good candidate to construct a $ZnMn_2O_4$/porous carbon framework through the template synthesis of a 3D porous carbon framework and incorporation with $ZnMn_2O_4$ (Figure 22) [82]. Asphaltene-based carbon fibers, due to their lower cost, lead to the fabrication of inexpensive LIBs for clean energy production.

It was shown that high energy and power values can be acquired from built electrochemical double-layer supercapacitor (EDLS) cells extracted from asphaltene precursors [83]. N, S-codoped activated carbon extracted from the asphaltene has been prepared and characterized to be used as an electrode material for an electric double-layer capacitor. The derived activated carbon contained both nitrogen (1.17 wt%) and sulfur (0.32 wt%) with a high surface area of 2558 m^2/g and a mesopore volume of 0.98 cm^3/g compared to the raw asphaltene. The asphaltene-based activated carbon delivered a high specific capacitance of 128 F/g at 0.5 A/g in 1 M tetraethylammonium tetrafluoroborate electrolyte with acceptable fatigue stability after 5000 cycles. Therefore, asphaltene-based carbon is able to be used as an electrode material to fabricate high-performance and efficient supercapacitors [84]. Asphaltene was used as a precursor to synthesize porous carbon fibers to be used as an electrode material for high-performance supercapacitors with superior capacitance related to the synergistic effects of the high specific area and abundant micropores of porous carbon fibers [85].

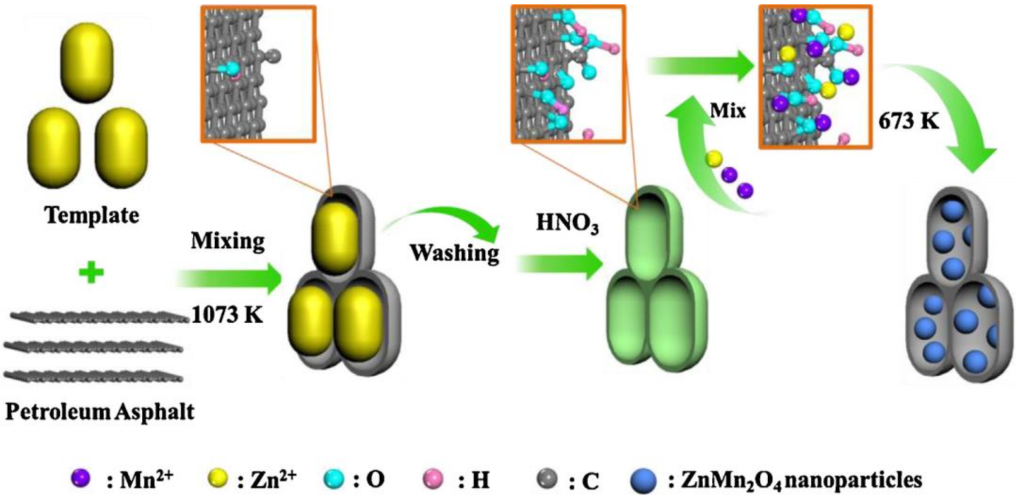


Figure 22. Schematic synthesis of 3D porous carbon framework made of asphaltene and incorporation with $ZnMn_2O_4$ (reprinted with permission from Ref. [82]).

10.1.2. Oil and Gas Absorption

The natural graphene of the raw asphaltene can be utilized to prepare a graphene–polyurethane sponge (GPU) to separate oil from water through a facile and inexpensive route of dip-coated sponge carbonization. In this process, low-value petroleum asphaltene and polyurethane sponges were used, respectively, as the dip-coating reagent and template (Figure 23). The GPU presents an excellent oil absorption performance, which is higher than other oil absorbents, as well as good recyclability. It also can be used in the pollution control of split oil [86].

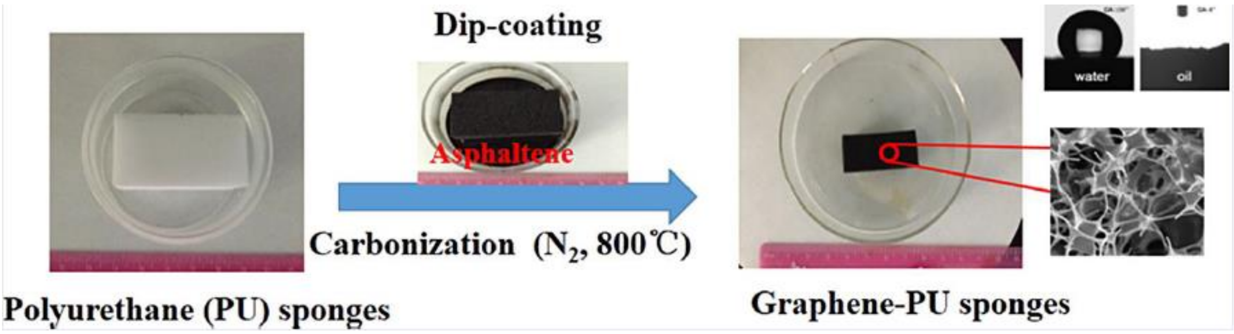


Figure 23. High-quality asphaltene-based graphene–polyurethane sponges (GPU) as absorbent (reprinted with permission from Ref. [86]).

Asphaltene, as a low-cost and abundant crude oil by-product, has also the potential for the production of high-quality carbon nanomaterials for the application of gas separation. It was found that asphaltene can be used as a precursor for the fabrication of microporous activated carbon absorbents to capture CO_2 [87]. A novel nitrated asphaltene-derived absorbent (Asf-Nitro) was produced using facile isolation and modification procedures. Asf-Nitro absorbent presented superior dispersive interactions (197.50 ± 1.12 mJm^{-2} at 423 K) in comparison to unmodified asphaltenes [88]. Nitrogen-doped asphaltene-based porous carbon nanosheets have an excellent ability to absorb CO_2 because of their developed pore structure and surface nitrogen-containing groups [89]. Hence, abundant and economically low-value asphaltene obtained from the petroleum industry could be a valuable source for the production of a variety of low-cost and highly effective gas absorbents and separators in various industrial applications.

10.1.3. Insulation

Asphaltene-based carbon fibers can be used for the thermal insulation of oil pipelines. A formation of asphaltene-based carbon fiber reinforced resin and paraffin layer can be utilized for oil pipelines in permafrost, and it can provide (1) anti-corrosion insulation and (2) thermal insulation because of the low coefficient of thermal conductivity of the asphaltene-based carbon fibers [90]. Therefore, asphaltene-based carbon fibers may be considered as a replacement for PAN-based carbon fibers for both structural and functional applications.

10.2. Structural Composites

In addition to the widespread use of carbon fibers in aerospace structures, their use in the automotive industry has increased dramatically due to increasing demand for fuel-efficient and lightweight vehicles meeting the new emission standard set by the European Union (95 g CO_2/km) and the United States (114 g CO_2/km) for 2020 [91,92]. The lower grades of carbon fibers than those used in the aerospace industry can be utilized in the automotive industry. Carbon fiber-reinforced composites can decrease the weight of automotive components by up to 60% and fuel consumption by up to 36–84%. However, the high cost of carbon fibers (about USD 18–35 per kg) is a barrier to the fabrication of automotive parts [93]. If we could decrease this cost to about USD 11–15 per kg, using carbon fiber-reinforced composites will be economical for automotive industries. Carbon fiber-reinforced composites in automobiles can be used as primary and secondary structures such as drive shafts, suspension parts, bumpers, dashboards, other interior components, etc. Hence, asphaltene-based carbon fibers as low-cost carbon fibers can be used as lightweight reinforcement for automotive composites.

Carbon fiber-reinforced composites can be used in building and construction as components of reinforced concrete or heat-resistive insulation. Fiber-reinforced polymer composites are an effective means for strengthening shear-deficient reinforced concrete flexural members. Asphaltene-based carbon fibers, due to their lower cost as well as relative strength and stiffness, can be a good replacement for carbon fibers used in building applications.

Moreover, carbon fiber-reinforced composites are widely used in the fabrication of medical prostheses and implants. For example, prosthetic rehabilitation costs USD 5000 to USD 50,000 and requires replacement every 3–5 years due to wear and tear [94]. Hence, low-cost asphaltene-based carbon-fiber reinforced composites are promising carbon fibers for medical applications to reduce the costs of prosthetic rehabilitation and implantable devices.

In addition, a coupling of structural and functional applications of asphaltene-based carbon fibers could be used in the construction of smart laminated composite structures with both core laminated composite structures and integrated piezoelectric patches made of asphaltene-derived carbon fibers for the applications of energy-harvesting and structural health monitoring [95–105].

Therefore, at the initial development of asphaltene-based carbon fibers, due to their low cost of processing, they can be a good candidate to be utilized in low-performance structural applications as the replacement of other existing fibers.

11. Innovation's Value Proposition

To have high-quality and low-cost carbon fibers, it is suggested to blend PAN with asphaltene for electrospun carbon nanofibers (CNFs) and blend thermal plastic polyurethane (TPU) with asphaltene for melt-spun carbon fibers. For electrospun nanofiber, it can be applied as continuous non-woven fabrics in composite form. PAN/asphaltene nanofiber can be directly electrospun without the pre-treatment or a slight treatment of asphaltenes, and the CNFs diameter is around 500 nm. PAN/asphaltene could have a higher surface area with good flexibility, and it can be applied as binder-less and free-standing carbon electrodes for different energy storage devices such as supercapacitors or batteries. The electrochemical performance could be further enhanced through the activation process. Electromagnetic interface (EMI) shielding is also a promising application for the PAN/asphaltene electrospun nanofiber. The application of PAN/asphaltene CNFs on energy storage devices and EMI shielding could create new paths of applications and opportunities for asphaltene-based carbon fibers.

The asphaltene/polymer blending electrospun and melt-spun carbon fibers can provide various carbon fiber forms from continuous non-woven fabrics to milled fibers with the fiber diameter ranging from 500 nm to the micron level. The carbon fiber properties can also be tailored and modified through tuning the asphaltene/polymer blending ratios or modification depending on the requirement of the end-users. The combination of asphaltene–polymer carbon nanofiber and melt-spun/melt-blown carbon fibers can increase the versatility and options of the asphaltene-based carbon fiber products to adapt for different applications. Accordingly, low-cost fabrication with various fiber diameters makes asphaltene-based carbon fibers an ideal candidate to create carbon fiber-reinforced composites for different applications by convincing clients to pay for this newly developed carbon fiber.

12. Market Potential Analysis

Since a newly developed carbon fiber derived from petroleum asphaltene is introduced, its market potential should be investigated before commercialization. In the market potential, performance (P) and cost (C) are two main parameters that should be considered carefully. Any new material commonly presents enhanced performance with higher cost or is cheaper with lower performance. To have an accurate analysis, a market potential diagram is needed. Figure 24 shows a trade-off plot with the market potential analysis comparing the asphaltene-derived carbon fiber with existing reinforcing fibers on the market based on their cost and performance. By producing asphaltene-derived carbon fibers with composite tensile strength: 50–500 MPa, composite elastic modulus: 50–100 GPa, and composite electrical conductivity: >5 S/cm, we can compete with other fiber-reinforced composites as well as lowering the fabrication processes and costs.

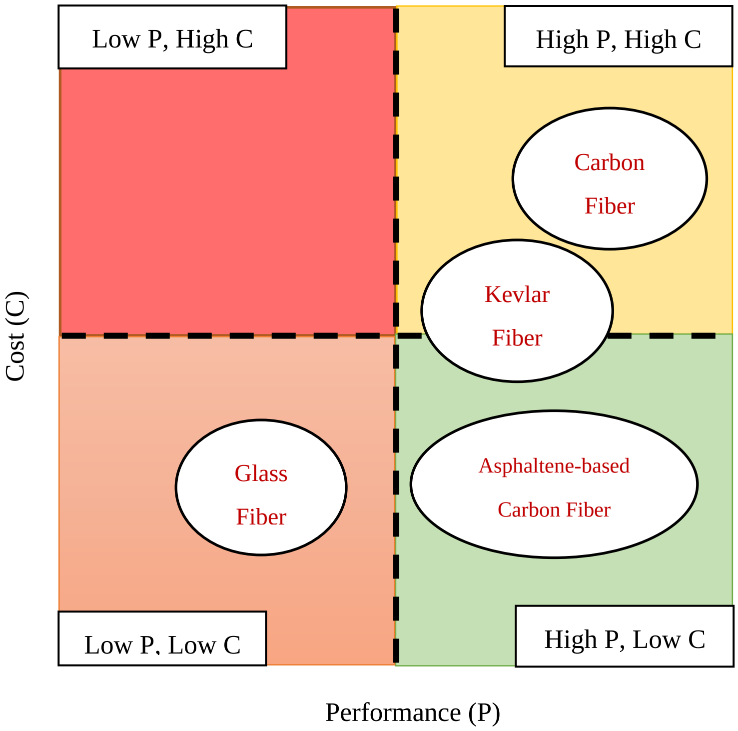


Figure 24. The cost/performance assessment for reinforcing fibers using a market potential diagram.

13. Target Market Size

In Table 3, a comparison between three widely used reinforcing fibers is displayed in view of their applications, cost, performance, annual growth rate, and market size.

Table 3. Target application and market assessment of typical reinforcing fibers.

Fiber	Application	Cost per Kilogram	Cost / Performance	Compound Annual Growth Rate (CAGR)	Size of the Target Market
Carbon	Aerospace, Civil Engineering, and Motorsports	USD 35	High/High	8.6%	USD 3.7 billion in 2020 USD 8.9 billion by 2031
Aramid (Kevlar)	Telecommunication, Aerospace, and Mechanical Rubbers	USD 23	Medium/Medium	7.5%	USD 3.28 billion in 2018 USD 5.78 billion by 2024
Glass	Automotive, Construction materials, Insulators, Oil and Gas, Boat hulls	USD 2	Low/Low	6.8%	USD 65.9 billion in 2019 USD 91.4 billion by 2024

Carbon fibers have several advantages in comparison to other fibers such as high tensile strength, high stiffness, high chemical resistance, low weight, low thermal expansion, and high-temperature tolerance. These outstanding properties have led to carbon fibers having very popular applications in aerospace, civil engineering, and motorsports. However, they are relatively costly in comparison to similar fibers such as plastic fibers and glass fibers. The global carbon fiber market size is expected to grow from USD 3.7 billion in 2020 to USD 8.9 billion by 2031 with a Compound Annual Growth Rate (CAGR) of 8.6%. Increasing demand from aerospace and wind energy industries is expected to make the growth of the market from 2021 to 2031 [106].

Aramid (kevlar) fibers as synthetic polymers have unique properties such as low density and high strength bearing capacity and can endure corrosive environments and very high temperatures. Aramid fibers are on average five times stronger than steel, without melting point, functorially efficient between 400 and 600 °C, and with dielectric properties. Due to these unique material properties, aramid fibers can meet the requirements in industries such as aerospace, telecommunication, and mechanical rubber goods, among others. These fibers are commonly utilized for protection and security applications due to their low density, thermal resistance, and high load-bearing capacity. The aramid fiber market size is estimated at USD 3.28 billion in 2018 and is expected to reach USD 5.78 billion by 2024 at a CAGR of 7.5%. By volume, the aramid fiber market was estimated to be 96.8 kilotons in 2018 and is projected to reach 149.5 kilotons in 2024. Due to regulations related to the reduction in carbon emissions and on the other hand, an increased need for lightweight and flexible materials for the automotive and aerospace industries, aramid fibers can be a great replacement and alternative to carbon fibers [106].

In 2019, the global market size of glass fibers was USD 65.9 billion, and it is expected to reach USD 91.4 billion by 2024 with a CAGR of 6.8% from 2019 to 2024. Glass fibers are widely used in automotive, construction and building materials, the oil and gas industry, boat hulls, etc. The glass and especially synthetic fibers market is increasing due to the rise in the demand for high-performance and lightweight materials globally [106].

Although carbon fibers have higher performance than Kevlar and glass fibers, their market is lower. However, the interest to use carbon fibers is increasing with a higher CAGR (8.6%) than Kevlar and glass fibers. Therefore, by producing low-cost asphaltene-derived carbon fibers with relatively high stiffness and strength and lower density, it will be able to at least catch the market of other cheaper and low-performance reinforcing fibers (such as glass fibers) as well as deliver high-performance and lighter weight fiber-reinforced composites.

14. Conclusions

This paper reviewed and discussed the production of carbon fibers from different precursors, from PAN to petroleum asphaltene (a new precursor), in comparison to other existing fibers on the market. Existing developed reinforcing fibers such as carbon fiber, Kevlar fiber, and glass fiber present different levels of performance and cost, and they are chosen based on the needs of clients. Although performance is the most important parameter for all clients, the cost always becomes a limitation for them in purchasing high-performance reinforcing fibers such as carbon fibers. If we reduce the cost of high-performance fibers by mitigating some unnecessary properties, at least for functional applications, we can deliver lightweight components to the clients which have a high impact on the performance of the final products such as lighter batteries in electric vehicles. Using inexpensive precursors from natural resources such as petroleum asphaltene could be a solution to reduce the production cost of carbon fibers.

Petroleum asphaltenes are abundantly available, and they are much cheaper than PAN and pitch and can be a great candidate as a precursor to produce low-cost carbon fibers. However, we need to optimize the process of carbon fiber production from the asphaltene to have the same quality of PAN- or pitch-based carbon fibers for both functional and structural applications.

Producing low-cost asphaltene-derived carbon fibers, at the first step of development, can target low-strength fibrous composites used in functional components, i.e., molecular sieves, catalysts, electrical conductors, electrodes, fuel cells, batteries, supercapacitors, insulators, absorbents, gaskets, etc. which occupied extensive markets. Then, as a long-term plan, the mechanical and thermal properties of asphaltene-based carbon fibers can be enhanced to be utilized in thermoset matrices for structural applications such as aerospace, marine, oil and gas, automotive parts, railway, pressure vessels, medical implants and prostheses, sports and leisure goods, etc. by satisfying the design requirements which leads to arousing the interests of industrial sectors to invest in this newly developed carbon fiber with relatively high performance and lower cost of production than typical carbon fibers.

Author Contributions: Conceptualization, data curation, investigation, data analysis, visualization, writing, and original draft preparation, H.B.; supervision, funding acquisition, writing review and editing, Y.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Alberta Innovates with grant number 202103138.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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