



Carbon-Fiber Composites: Development, Structure, Properties, and Applications

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Abstract

Carbon fibers are stiff and possess high strength comparable with that of high-strength steel. They are embedded in a ductile low-strength material which binds them together to form a carbon fiber composite. Improved properties are developed from a blend of the carbon fibers and the matrix material which are not achievable from each component used individually. Carbon fiber composites

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(CFCs) are light and strong and are replacing existing heavy alloys or metals across various engineering sectors. Non-uniform properties of CFC from a direction to another remain a challenge. Addressing anisotropy in CFC gives a premise for varying orientation of carbon fibers that gives rise to different carbon fiber plies which are tape, weaving, and knitting plies. Carbon fiber is sourced from conventional fossil resources including coal and natural gas, which are not renewable and their exploitation poses threat on ecology and human comfort. Recent emerging waste-to-wealth technology reveals extraction of crop fiber from remnants of agricultural creations which are carbon-based and are possible replacement for carbon fiber in composite fabrications. Therefore, this chapter covers an overview of CFC, development, structure, and applications. Introduction of plant remnants for replacing carbon fiber in composite fabrication is part of this discussion.

Keywords

Carbon · Fiber · Composite · Plant remnants · Development

Introduction

Various artifacts in our environment are products of various engineering designs which apply creative, smart, and new materials that possess special properties to withstand dynamic environmental constraints. Environmental elements such as solar radiation, mild and aggressive atmospheres are dynamic in nature and cause variation in the technical functionalities of the artifacts. Environmental challenges confronting various artifacts are being solved over the years through the emergence of advanced materials of which CFCs are some of them. Carbon-fiber composites are inevitable materials possessing properties not common with conventional materials. This class of materials contains carbon fiber as reinforcement in metals, polymers, or ceramics [1]. Aluminum possesses resistance to atmospheric corrosion, high ductility, and lightweight, making it suitable for numerous outdoor applications but its relatively low strength and stiffness are challenges. It has served as the matrix for carbon fiber in producing a set of aluminum-based metal matrix composites [2]. Carbon fiber aluminum composites possess excellent mechanical, electrical, and antiaging properties and are employed in automotive industries, as vehicle panels for replacing traditional heavy steels [3]; in construction as building materials serving as an alternative to steel and cements [4], marine components, aerospace materials; and in electrical industries as electrical conductors [5]. Both thermosets like epoxy resin, polyester, cyanate ester [6], and thermoplastics such as poly lactic acid [7], polyethylene [8], and polypropylene [9] are matrices for fabricating carbon fiber polymeric composites. Thermosets have the advantage of higher thermal stability than thermoplastics but the latter have excellent thermally activated softening and remolding properties unlike the former. Carbon-fiber polymeric composites are many due to various choices of the matrix, leading to addition of new polymeric

composite to the literature through research and development. They offer highly demanding properties of aerospace application like feasibility to be produced in multiple, shapes or forms [10], lightweight, and corrosion resistance; therefore, they are used as fuselage, communication satellite, and other air/spacecraft materials. Carbon fiber/epoxy fuselage can withstand higher level of humidity than aluminum and produces better conducive environment for passengers and cabin crew. Moreover, carbon fiber composites containing either epoxy, polyethylene, or polypropylene are used as automotive components such as bumper and interior panels contributing to vehicle lightweight for fuel efficiency and CO₂ reductions [11]. Carbon-fiber/carbon (C/C) is the most common ceramic composite. Others are C/C-SiC and C/C-Al₂O₃ having enhanced toughness and resistance to thermal shock. It is used for high temperature applications such as aircraft brake, high-performance vehicle brake, screw fastener, electrical resistant heating element, and dies for metal forming due to its refractories and excellent wear resistance [12].

Applications of CFC are reflections of their properties suitable for demanding design requirements of the application areas. The properties depend on structures developed during their productions which are a function of interactions between the carbon fiber reinforcement and the matrix. Form of carbon fiber (continuous or chopped) and their orientation are key parameters of consideration in investigating carbon fiber interaction with the matrix which in turn influences the CFC properties. A unidirectional carbon fiber composite has high strength along the longitudinal direction but the transverse direction strength is very low [13]. The carbon fiber composite's anisotropy is a problem in case of sudden increase in strength along transverse direction in a service environment. This can claim lives especially in sensitive applications such as aerospace, automobile, and marine industries where CFC are extensively used for various components. Carbon fiber multiple orientation approach through weaving [14], knitting, or ply stacking at different angles of orientation like 0, 45, 90, -45, and -90 in a single fiber laminate reduces the anisotropy since the approach offers almost uniform strength in multiple directions. Although the approach minimizes the directional properties, the woven fabrics are not suitable for high-performance structural applications but aligned fiber sheets because of unavoidable bending of the carbon fiber in the woven fabric causing non-uniform properties along fiber axis and the transverse direction since fiber overlap and bend around one another during weaving [15]. Moreover, CFCs would have gained wider applications besides high-performance structural applications but high cost of fiber is a constraint [12]. Besides, carbon fiber is produced from polyacrylonitrile, pitch, rayon, coals, or petroleum. Polyacrylonitrile is a petrochemical, sourced from non-renewable petroleum. Continual exploitation of coals and petroleum for producing carbon fiber and other useful materials will not only disturb ecology balance but also impact exploited area negatively. Therefore, finding alternative reinforcement that can favorably compete with carbon fiber in properties, with less cost of production, renewable resources with no adverse impact on society is imperative. This present contribution is aimed at brief discussion on carbon fiber, CFCs, and introduction of renewable environmental materials which are potential reinforcing fiber.

Carbon Fibers

Fiber is a natural or artificial material having longer length than width. In composite technology, it is reinforcement to carry external pressures (stresses) imposed on the composite. It is stronger than bulk materials mainly because of its alignment and few or no flaw in it due to its small diameter [16]. A good fiber network is an important parameter for excellent load-bearing performance of the fiber. That is, strong adhesion is inevitable between fiber and the matrix to connect all fiber together and act as a single network for a rapid load transfer, distribution, and sharing among the fiber through the matrix. This prevents stress localization at a point that may lead to local composite failure. Fiber occurs in different types including glass, carbon, aramid, boron, spectra, silica, quartz, poly lactic acid, and high molecular polyethylene fiber. Development of glass fiber makes an onset of fiber synthesis for producing lightweight high-strength/stiffness materials for high-performance structural applications like automotive, rail, truck, sea/water transport, building construction, commercial aircraft, racing craft, military aerospace, rocket, and missile applications. E-glass fiber containing calcium aluminoborosilicate is very cheap and has lower mechanical properties than S-glass fiber having higher proportion of alumina. Insufficient stiffness of glass fiber required in some of the high-performance structural applications, like in aircraft, missile, and space applications, caused research to look for stiffer fiber and led to development of carbon fiber, gaining widespread applications in fabricating advanced materials for various applications. Fibrous boron is stiffer than carbon fiber but its higher cost than that of carbon fiber has limited its application. Carbon fiber refers to the fiber produced from carbonaceous resources like petroleum, coal, polyacrylonitrile (PAN), rayon, and pitch. It is stiffest among metal, polymer, and ceramics and stronger than steels having maximum strength. They have different mechanical properties [17] perhaps depending on carbonaceous resources from which they are produced and methods of production. Tensile strength of carbon fiber produced from pitch varies from 2.2 to 3.5 GPa and its tensile modulus ranges from 490 to 830 GPa. Low tensile strength of the pitch-based carbon fiber limits their applications in high-performance structural applications [16] despite their highest tensile modulus when compared with those of other materials as shown in Fig. 1f. PAN-based carbon fiber has better tensile properties because of its high tensile strength (4.14–5.17 GPa) and moderate tensile modulus (280–450 GPa). Dimensionally, carbon fiber has longer length than width or diameter (Fig. 1a) and is continuous (Fig. 1b) or discontinuous [9]. The latter has a length that runs from head to tail of the composite ply either along longitudinal or transverse direction while the former can be chopped (Fig. 1c) [18], milled fiber (Fig. 1d), or nanofiber (Fig. 1e). Chopped fiber is a random fiber having a length not covering the entire length of the composite preform and distributes randomly within the matrix.

Milled fibers (1d) are particles obtained through ball milling, exist in different shapes due to carbon fragments produced from attrition or friction and fuse together due to Van der Waal's force to form carbon agglomerate during the milling process [19]. Milled fibers are dissolved in absolute ethanol [20] to break up agglomerates

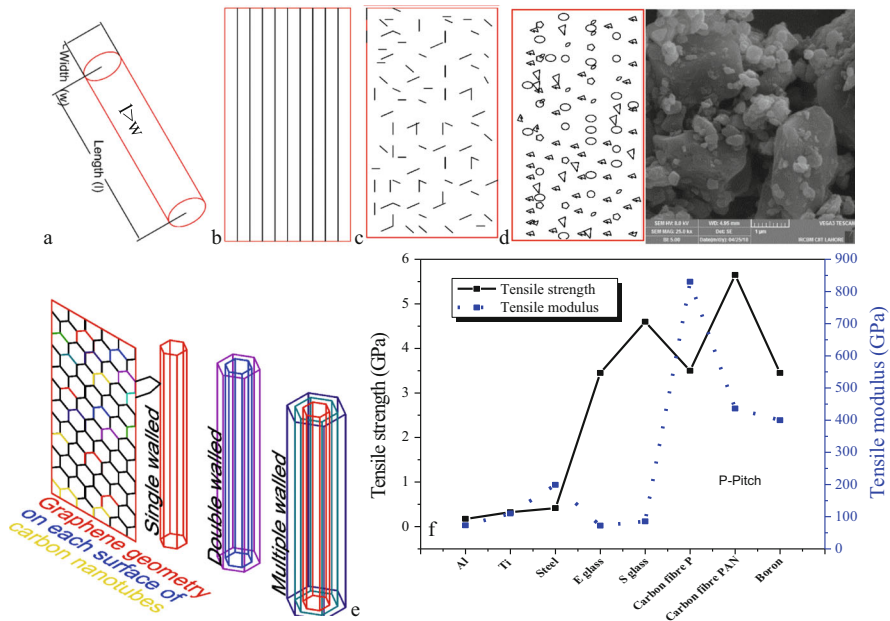


Fig. 1 Carbon: (a) description of carbon fiber using length and width/diameter, (b) continuous fiber, (c) chopped discontinuous fiber (d) computer/SEM image of milled discontinuous fiber, (e) single, double and multi wall carbon nanofiber/tubes with graphene sheet revealing geometry of graphene making up the nanofiber. (f) Comparison of tensile properties of carbon fiber with those of aluminum (Al), titanium (Ti), steel, glass, and boron fiber, pitch-based carbon fiber has the highest tensile modulus and PAN-based carbon fiber has the highest strength

and produce isotropic composites because of their ease of dispersion in the matrix unlike directional properties associated with other forms of carbon fibers, though continuous fibers are the most effective in matrix strengthening because of their continuity throughout the composite ply. The carbon nanofibers are hollow tube (Fig. 1e) with diameter less than 1 nm. Besides being used as reinforcement for developing various composites, soluble carbon nanotubes are used in medicines, as means of protein transport and drug delivery [17]. Carbon fibers are aligned along a single direction to form a unidirectional ply. Since the carbon fibers are strong along their axis (longitudinal direction) but weak in perpendicular direction, the unidirectional carbon fiber ply has varied properties from longitudinal to transverse directions. Directional properties are reduced in bidirectional fiber plies in which a set of aligned carbon fibers are arranged perpendicular to each other through weaving or knitting (Fig. 2). Quasi-isotropic properties are achieved through weaving or knitting in multiple directions (Fig. 3) to form carbon fabric or cloth [21]. Carbon fibers are weaved by lapping and or bending a fiber over another fibers. Knitting involves joining fibers in different directions using fastener or stitches. Stitched carbon fabric is called non-crimp fabric because of absence of hump/crimp in the woven fabric rendering the woven carbon fiber fabric unsuitable for high-performance structural

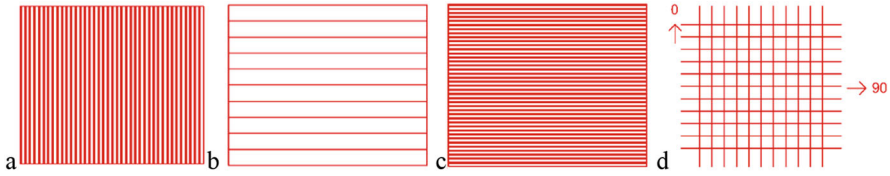


Fig. 2 Continuous carbon fibers: (a) transverse unidirectional ply, (b) longitudinal unidirectional ply having few carbon fibers, (c) longitudinal unidirectional containing many aligned carbon fibers, (d) bidirectional ply developed from both transverse and longitudinal plies

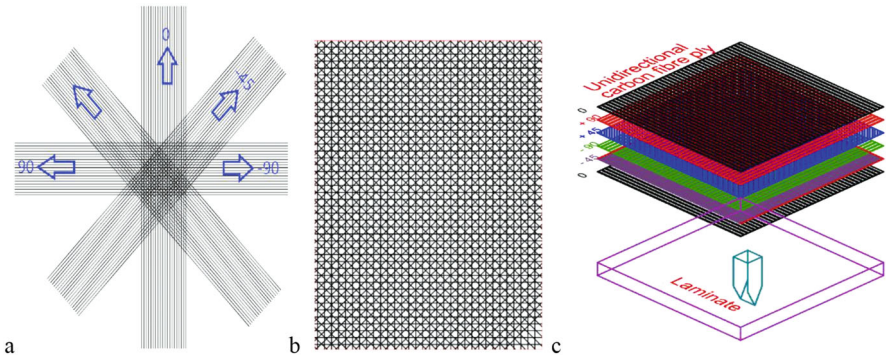


Fig. 3 Carbon fiber fabric and stacked laminate. (a) Unidirectional carbon fiber plies at different angles of orientation, (b) fabric produced from the unidirectional plies through weaving or knitting, (c) carbon fiber laminate synthesized unidirectional plies by stacking at different angles

applications like aerospace, automobile because of non-uniform properties. In addition, stacking of unidirectional or bidirectional carbon fiber ply (sheet) [22] at different angles of orientation from 0 , -45 , -90 , 45 , 90 , and 0° produce the carbon fiber laminates approaching property isotropy (Fig. 3c).

Synthesis of Carbon Fibers

Carbon fibers are manufactured from different materials (precursors) like PAN, pitch, rayon, coal, and petroleum causing variations in methods of their production, properties, and cost of production. Carbon fiber production from rayon is uneconomical because the yield of carbon fiber after carbonization is small and the process requires stretching the carbon fiber at elevated temperature to the appropriate diameter. This is expensive to achieve. Currently, approximated 90% carbon fiber is produced from PAN and the remnants are from pitch. Synthesis of carbon fiber from PAN is achieved by subjecting the precursor to spinning, stabilization, and carbonization [23].

Spinning

PAN can be dry or wet spun. Large diffusion gradients from rapid solvent removal in the dry spinning results in carbon fiber whose shapes are seriously influenced by the diffusion gradients. In wet spinning, there is no diffusion gradient due to application of coagulant for solvent extraction from the polymer. In the wet spinning, PAN precursors containing acrylonitrile and methyl acrylate, methyl methacrylate, vinyl acetate, hydroxyl ethylene or vinyl chloride-itaconic acid are mixed with dimethylacetamide to form polymer solution which is forced through a die tiny orifice of the spinneret into a chamber where it coagulates using ethylene alcohol and solidifies into fiber. Coagulation is the solvent extraction from the polymer and its rate influences the shape of the final fiber like the dry spinning process. Moreover, structure and properties of the as-wet spun fiber are affected by temperature, concentration, and fluid circulation rate in the coagulation chamber [16]. Each of the additive to acrylonitrile is for enhancing spinning properties of the precursor, fiber properties, and means of producing the fiber with large carbon content after carbonization. Spinning of the pitch precursor starts with heating at a temperature between 200 and 350 °C to raise its viscosity to a value between 10 and 200 poises. Pitch decomposes at 350 °C. The spinning temperature in excess of 200 °C is preferable since the spinning temperature is a measure of maximum temperature which as-spun pitch fiber is subjected to, in the stabilization process. Upon the required temperature, the pitch precursors can fall into varied processing window described as lowest window having 100% pitches obtained from coke or petroleum and the maximum window containing mixture of spherical isotropic and anisotropic transformed pitches, which need to be separated before spinning. The spherical isotropic pitches may produce weak discontinuous fibric thread after spinning and since stabilization rate of the isotropic as-spun pitch fiber is different from that of the anisotropic fiber, non-uniform stabilization occurs and it is difficult to obtain optimum properties of the pitch fiber.

Stabilization

Stabilization is the heating of the spun fiber in air at temperature between 200 °C and 300 °C for at least 30 min to convert linear atomic bond of polymeric thermoplastic fiber to polymeric thermosetting ladder bond which can withstand heating and maintain its geometry during carbonization process. The process is sometimes initiated with reactive copolymer catalyst like itaconic acid [16]. During heating, the as spun-fiber picks up oxygen leading to structural rearrangement with the formation of new bonds and higher thermally stable geometrical patterns. Stabilization of the as-spun PAN fiber is like that of the anisotropic as-spun pitch fiber as both release a great amount of heat to the surrounding, that is the process is an exothermic. Rate of oxidation reaction must be controlled and uncontrollable high temperature that may lead to melting of fiber must be prevented to prevent hazards. Therefore, stabilization is normally carried out in oxidative-limiting amino/amine or inert gases

(NO/N₂O, HCl/O₂, Br₂/O₂) containing medium. However, there are differences between as-spun PAN and pitch anisotropic fiber stabilization. Many chemical reactions occur in the stabilization of the as-spun fiber while in the pitch anisotropic fiber, there are cross-linking reactions.

Carbonization

This is the heating of stabilized PAN or pitch fiber in the absence of air to temperature between 1000 °C and 3000 °C [17]. Air absence is paramount to prevent fiber burning at high temperatures and is achieved during the carbonization by sealing the entry and exit of the furnace and keeping furnace inner pressure higher than outside air pressure. Emission of carbon (C), oxygen (O), hydrogen (H), and nitrogen (N) containing gases like H₂O, CO, CO₂, NH₃, and HCN with free N₂ takes place up to 1000 °C. Nitrogen gas and its compounds are evolved from the PAN fiber alone. This marks a difference between PAN and pitch fiber carbonization. However, in the typical carbonization of stabilized PAN fiber; at initial heating stage up to 360 °C, there is a cyclization of PAN fiber involving evolution of NH₃ and HCN in large amounts. Up to 450 °C; emission of NH₃, HCN, H₂O, acrylonitrile, and propionitrile takes place [16]. Evolution of free N₂ occurs from 700 °C and up to 1000 °C, the whole carbonization process can be described as loss of precursor materials due to gas evolution such that at the temperature, only 5.8% by weight of N₂ remains in the fiber and more than 50% PAN precursor has distilled off. Also, there is a transformation from viscoelastic stabilized fiber to brittle fiber. Remaining N₂ is eliminated during heating above 1000 °C up to 1500 °C and carbon sheets are totally transformed from PAN molecules. The whole carbonization of the stabilized PAN fiber can be described as dehydrogenation and denitrogenation processes. The former occurs at low temperature while the latter takes place as the temperature increases up to 1500 °C. In heating above 1500 °C at a high rate to 2500 °C for duration not more than a minute, there is no more gas evolution but structural rearrangement that leads to transformation of the carbonized fiber to the graphitized fiber. However, it is worth noting that the PAN fiber is naturally not graphitizable while the pitch fiber being graphitizable has better oriented crystal structure, higher stiffness, thermal conductivity, lower coefficient of thermal expansion, and is more stable with molten silicon. The change in structure causes graphitization of the stabilized pitch fiber enhances the thermal stability but there is no great improvement in the tensile strength.

Natural Fiber

Carbon fiber is produced majorly from PAN and pitch. Moreover, acrylonitrile, a monomer for PAN synthesis, is produced by SOHIO process which is the catalytic oxidation of ammonia and propylene in a fluidized bed reactor at a temperature range 400–510 °C and a pressure range 0.05–0.2 Nmm⁻² [24]. Besides the process, the

acrylonitrile is produced by green synthesis from lignin-cellulosic materials, glutamic acid, or glycerol which are obtainable from renewable resources/biomass. However, an interest here is not the description of method for producing acrylonitrile but to establish raw materials like propylene, ammonia, and oxygen for its production. Ammonia is sourced naturally from decaying biomass. Propylene is an olefin (petrochemical) which is obtained from fractional distillation of petroleum. Pitch originates from fractional distillation of petroleum and a byproduct of destructive distillation of coal. These imply that both PAN and pitch fiber are sourced from fossil fuels which are nonrenewable. Besides ecological deterioration of exploited areas impacting the society negatively, nonrenewable resources will vanish upon continual exploitation. Therefore, alternate source of carbon fiber or its replacement with competing fiber is very important. However, annual agricultural turnouts to cater for increasing teeming human populations release large amount of wastes disturbing our immediate environments. Banana stem/fruit peel, Luffa, Sisal, Flax, Ramie, bamboo stalk/stem, pineapple leaf, hemp, coconut choir, ramie, flax, rattan, jute, palm kernel, rice, vine, kenaf, wheat, barley, cotton, *Paraquetina nigrescens*, raffia palm, straw, and baobab (*Adansonia digitata*) in Fig. 4 are seed, leaf, stalk, and stem depending on one plant or other and they are inherently sources of continuous fiber

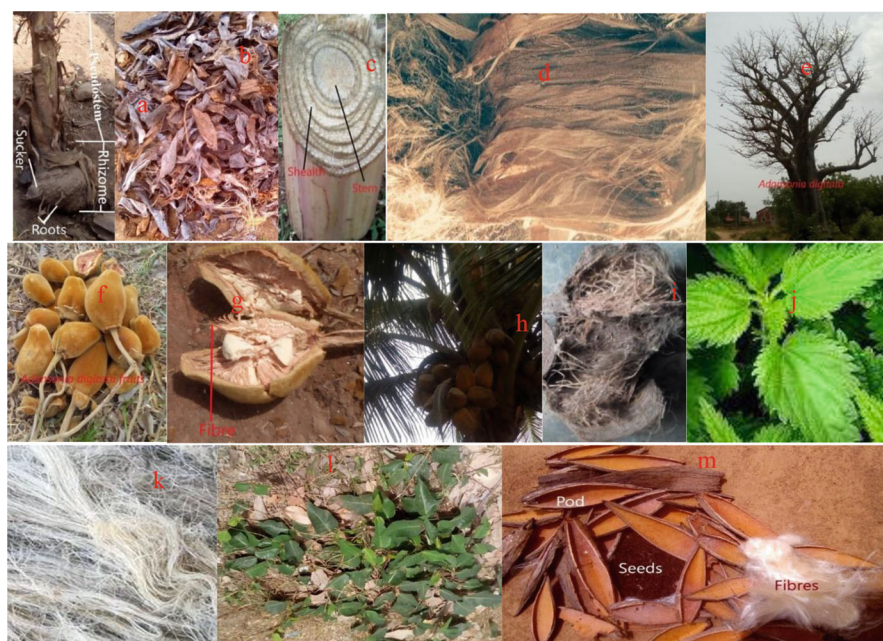


Fig. 4 Agricultural resources with emanating fibers: (a) banana plant showing different parts, (b) banana peel fiber, (c) banana pseudostem, (d) banana stem fibers, (e) baobab tree, (f) baobab fruits, (g) sliced baobab showing strands/fibers, (h) coconut plant, (i) coconut coirs, (j) nettle plant, (k) nettle fibers, (l) *Paraquetina nigrescens* plant, (m) *Paraquetina nigrescens* burst pods with seeds and fibers

like banana stem or random fiber such as *Paraquetina nigrescens*. They are lighter, having better thermal insulation and lower skin irritation than glass fiber. Their biodegradation after service expiration makes them environmentally friendly like carbon fiber. They are available in large quantities (wastes), renewable making them naturally replenishable. They are accessible as byproducts from agricultural productions with no environmental impact. Therefore, they are alternative to carbon fiber but their inferior mechanical properties are a challenge. Agricultural fibers are many because of numerous plants as many are yet to be discovered. They have different properties depending structure of the fiber, composition, parts of the plants from which the fiber originates and their maturity. Generally, all agricultural fibers contain cellulose, hemicellulose, lignin, and moisture. Strength of the agricultural fiber increases with high cellulose content and cellulosic microfibrillar angles which improve wettability of the fiber with a matrix. Banana fiber has 63–64% cellulose, 19% hemicellulose, 5% lignin, 10–15% moisture, 10–12° microfibrillar angle, and specific gravity of 1.35. The structural and physical properties of the banana fiber are different from those of other agricultural fibers like coconut coir/fiber having 32.65% cellulose, 7.95% hemicellulose, 59.4% lignin, 10–12% moisture, 30–40° microfibrillar angle, and specific gravity of 1.15. Tensile strength, modulus, and elongation of nettle fiber are 954–2234 MPa, 59–119 GPa, and 1.5–6% [23]. Those of other fiber starting with coconut fiber are 106–175 MPa, 4–6 GPa, and 17–47%; palmyra 180–215 MPa, 4.4–6.1 GPa, and 7–15%; sisal 568–640 MPa, 9.4–15.8 GPa, and 3–7%; banana fiber 54–754 MPa, 7.7–20 GPa, and 10.35%, pineapple 413–1627 MPa, 34.5–82.5 GPa, and 7–15%; cotton 287–597 MPa, 5.5–12.6 GPa, and 3–10%; jute 393–800 MPa, 10–30 GPa, and 1.5–1.8%; ramie 220–938 MPa, 44–128 GPa, and 2.38%; kenaf 284–800 MPa, 21–60 GPa, and 1.6% [25]; hemp 550–900 MPa, 70 and 1.6% [26–28], respectively. Differences in their mechanical properties are reflection in variation in their structures. This list indicates none of the agricultural fibers has tensile properties comparable with PAN carbon fiber having tensile strength of 2.5–5.65 GPa, modulus of 231–436 GPa [16], and 1.4–1.8% elongation [16, 26] and pitch carbon fiber having 2.2–3.5 GPa, 490–830 GPa, and 0.3–0.6%, respectively. This implies that various efforts toward replacing carbon fiber in sustainable composite development have not been totally successful despite numerous studies focusing on the subject [29]. Therefore, doors are open for additional research involving new approach. Since it has been established that every agricultural fiber contains cellulose, lignin, hemicellulose and other structural components like pectin, holocellulose, implying that agricultural fiber contains elements like H, O, N in addition to C, removal of other elements through dehydrogenation and denitrogenation at elevated temperature to produce renewable carbon fiber is a new research focus that has not been tapped. Also, the resulted renewable carbon fiber from the approach may have better mechanical and thermal properties than ordinary agricultural fiber and their properties can be comparable with those of PAN and pitch-based carbon fiber. Direct synthesis of renewable carbon fiber from biomass/agricultural fiber is envisaged rather synthesis of acrylonitrile from biomass through green synthesis that has been found in literature [30]. Alternatively, researchers can extend their studies to unexploited agricultural fiber focusing on

probable finding fiber having superior properties to the existing ones. Among unexploited fiber are baobab and *Paraquetina nigrescens* fiber. Baobab is a tree species belonging to Plantae Kingdom; Tracheophyte, Angiosperms, Eudicots and Rosids Clade; Malvales Order, Malvaceae Family, *Adansonia* Genus, and *A. digitate* Species; hence the botanical name *Adansonia Digitata*. The name *Adansonia* was after a French explorer and botanist Michel Adanson who observed baobab specimen in 1749 [31]. Baobab trees are bottle-shaped, 5–25 m tall, live for more than a thousand years, lose their leaves in every dry season (Fig. 4g) and have horizontal root longer than their height. It is found in most African countries in drier, less tropical climates. It is a source of food in Africa. The baobab fruit and leaf are edible; the fruit can be eaten fresh, to make a drink by dissolving it in water, used as smoothie and food ingredient. The leaves are rich in minerals, phytochemicals and are used in Northern Nigeria for preparing soup. Moreover, every part of baobab is medicinal and oil is extracted from their fruits [32]. When the baobab fruits are consumed, remnants include seeds and strands valuable as fiber. Currently, research on baobab fiber as engineering materials is scarce as there is no information on their structural, physical and mechanical properties to ascertain their potential as reinforcement for composite development. *Paraquetina nigrescens* plant (Fig. 4i) is found in Nigeria, Ghana, and parts of Senegal. It is an herbaceous perennial plant containing roots, leaves, latex, and bark. Leaf and stem of the plant contain saponins, tannis, cardenolides, anthraquinones, terpenoids, flavonoids, cardiac glycosides, and ascorbic acids [33]. Elementally, the leaf has Mg, Na, Pb, K, Fe, Zn, Ca, Cu, Mn, P, Ni, Cr, Cd, and Co. Fe has the maximum counts and the least count is found with Co [34]. Although Pb and Cd are poisonous, their contents are lower than benchmark (maximum level) recommended by the World Health Organization (WHO)/Food, Agriculture and Organization (FAO) [35]. Chemicals like myrcene, neral, Geranial, and α Gamascone are found in oil extracted from the leaf [36]. Extracts from the plant parts are used locally in the Southwestern part of Nigeria for treating gonorrhea, menstrual complication, rickets, diabetes, sickle cell anemia, diabetes, and sexual dysfunction. Moreover, extract from the leaf is a major component for preparing versatile medication (described in Nigerian's local language as "Aporo Egba Ijebu" interpreted as "Poison Killer of Ijebu tribe") for treating many health problems. Also, the extract is used as a tonic for blood replenishment, though these applications have been confirmed locally but their scientific documentations are rare. Recently, potential of *Paraquetina nigrescens* leaf extracts for treating paroxetine hydrogen chloride induced sexual problem and alloxan induced type-1 diabetes in rats were reported by [34, 37] respectively. Also root extract has been reported in [38] to treat induced sexual dysfunction in rats. Besides leaf, roots, stem, and bark, *Paraquetina nigrescens* plant bears inedible fruits having pods covering fiber and seeds (Fig. 4i). In a freshly harvested/burst fruit, fiber is packed together at one end by seeds before detachment by air blow/wind dispersing the fiber. The pods and fiber make *Paraquetina nigrescens* plant an important agricultural resource for engineering materials in addition to medicinal values of its other parts.

Visual examination and manual size determination using ruler reveals that *Paraquetina nigrescens* fiber is 5–6 cm long and threadlike. Scanning electron microscopic/

energy-dispersive X-ray spectroscopic analysis shows the fiber as a hollow cylinder with inner and external diameters of 69 and 81 μm (Fig. 5), respectively. The analyzed point reveals that *Paraquetina nigrescens* fibers contain carbon (C) and oxygen (O) having weight percent of 60.88 and 39.12% and atom % of 67.46 and 35.24% (Fig. 6a),

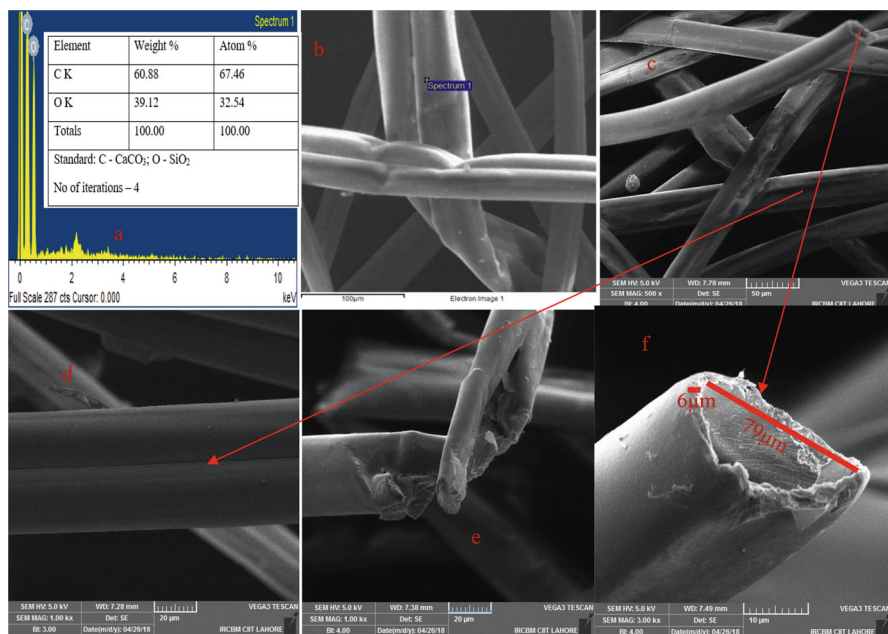


Fig. 5 SEM/EDX of *Paraquetina nigrescens*: (a) energy-dispersive X-ray spectrograph (EDX), (b) SEM showing the analyzed point for elemental identifications, (c) morphology at $\times 500$, (d) morphology at $\times 1000$, (e) morphology showing inherent defect at $\times 1000$, (f) morphology at $\times 3000$

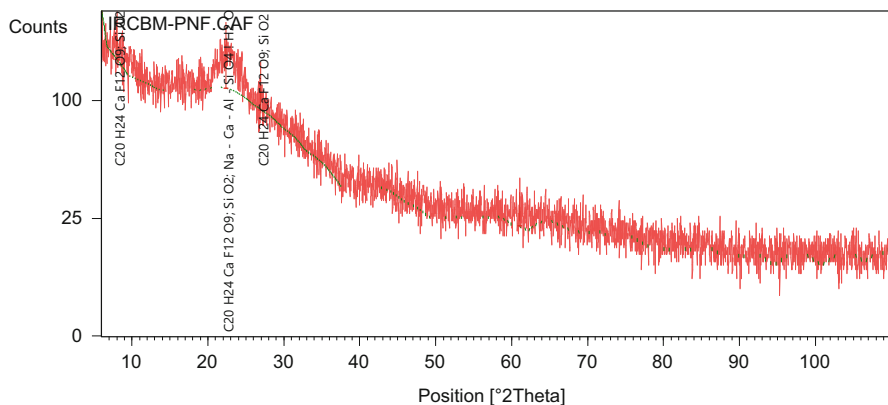


Fig. 6 X-ray diffractogram of *Paraquetina nigrescens* fibers

respectively. Both C and O represent various compounds like silicon oxide, sodium calcium aluminum silicate hydrate, and calcium (2,5,8,11,14-pentaoxodecane-O@2, O@5, O@8, O@11)bis(1,1,1,5,5,5-hexafluoro-2,4-pentadionate-O',O') as detected from X-ray diffraction analysis (Fig. 6). Length range (5–6 cm) of the *Paraquetina nigrescens* fiber falls within 100 nm–50 cm length range of the carbon nanotubes but their diameters (69–81 μm) are much longer than 0.8–20 nm range of the carbon nanotube diameters. Also, hollow cylindrical structures of the *Paraquetina nigrescens* fiber resemble that of the carbon nanotube. Upon similar structure of the *Paraquetina nigrescens* fiber with that of the carbon nanotube, it may be used as a water filter and vehicle for drug delivery system for targeting cancerous cells. Its longer diameter than that of carbon nanotube may accommodate higher drug quantities than the carbon nanotube. Solubility of drug vehicles or carriers in aqueous solution, cell penetration, and biocompatibility are fundamental to drug transport to aid their movement via the body, reduce the risk of blocking important body organ pathways and must not be toxic/harmful to body cells. Although different degrees of cytotoxicity have been associated with carbon nanotubes in varied forms [39], lipid functionalization of carbon nanotubes has been reported to enhance biocompatibility via reduction in cytotoxicity [40]. Establishment of the proposed applications of *Paraquetina nigrescens* fiber through research and development is needed. Therefore, mechanical properties, phytochemical screening, and biocompatibility investigations of the *Paraquetina nigrescens* fiber and comparison of results with properties of the carbon nanotubes are research focuses for interested researchers globally. Moreover, inherently chopped/random forms of *Paraquetina nigrescens* fiber make them valuable as discontinuous fiber for ceramic, metallic, and polymeric composite fabrications which may be useful for high-strength structural and non-structural applications.

Carbon Fiber Composites

Carbon-fiber composites are materials having carbon fiber as sources of strength and stiffness for load bearing and the matrix for toughening the composite, protecting and binding the carbon fiber [41]. Their properties are made to improve their performance and suit applications through variation of fiber contents, fiber orientation/directionality, and choice of matrix [42]. Matrices for developing CFCs are ceramics, metals, or polymers. Development of CFCs entails carbon fiber synthesis and processing of the carbon fiber/matrix mixture.

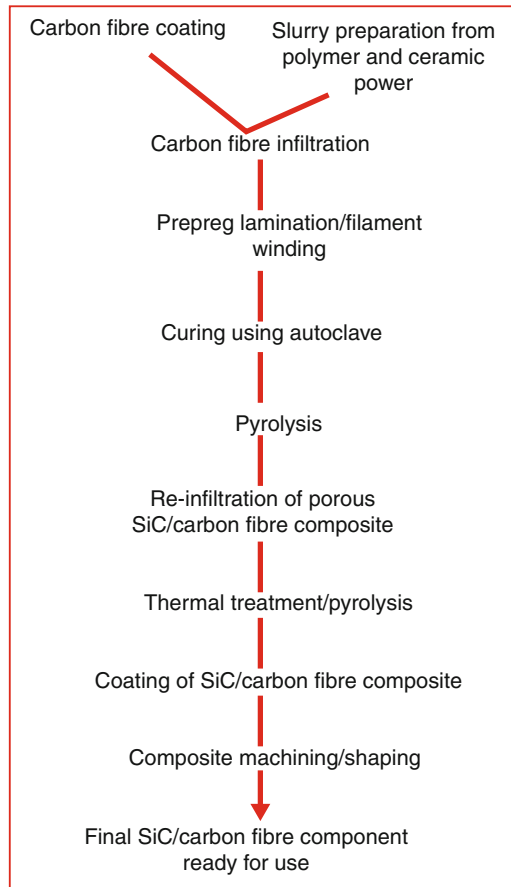
Carbon Fiber Ceramic Composite (CFCC)

These composites use ceramic materials like carbon, carbides, oxides, borides as infiltrator to fill pores within carbon fiber plies/preforms. They are different from metallic and polymeric composites where carbon fibers are load bearers because of much smaller strength/stiffness of the matrix. Both carbon fiber and ceramic fillers have comparable strength and stiffness such that if bond between the fiber and matrix

is strong, both act as load bearers. They have high stiffness, hardness, compressive strength, thermal stability, wear resistance, and low thermal expansion. Different types of infiltration techniques are used for manufacturing CFCC. Infiltration is a composite fabrication technique involving filling of pores within materials through interaction with liquid or vapor. It is melt/liquid-infiltration when pores interact with liquid and vapor infiltration when the interaction occurs with vapor. Liquid polymer, liquid silicon, isobaric/thermal vapor, and pressure/temperature gradient vapor infiltrations are employed in large industrial scales for fabricating CFCC. Chemical vapor infiltration for manufacturing carbon fiber/SiC composite involves anchoring carbon fiber preform in a furnace using tooling or temporary binding agent which is burnt off during the pyrolysis process. Vapor from precursor methyl-trichlorosilane on heating at 800–1100 °C decomposes on the surfaces of the carbon fiber preform to release SiC diffusing into the porosities within the carbon fiber preform under pressure of 30 kPa–100 hPa. Since this process takes place at constant temperature and pressure between the identified temperature and pressure ranges, it is regarded as isothermal/isobaric chemical vapor infiltration. The ceramic composite resulting from this process has high fracture toughness and excellent thermomechanical properties but the process is very slow. The temperature/pressure gradient process allows SiC liberation at high temperature and pressure, leading to SiC deposition at a high rate. This technique reduces processing time to 40–60 hours and produces thin composite with reduced porosity against months in the case of the isobaric/thermal chemical vapor infiltration and restricted geometry [43, 44]. Before SiC deposition, carbon fiber is coated with carbon deposits from decomposition of methane to provide good interphase between SiC and carbon fiber. This is to prevent degradation in carbon fiber properties due to their reaction with SiC. The product from the technique is machined to give the actual shape for intended applications [42].

In polymer infiltration, polysilane or polycarbosilane precursor is decomposed to SiC at 1100–1600 °C in the absence of air. The SiC is pressurized to fill porous spaces within the fiber preform. Several pyrolysis and infiltration cycles are performed to obtain product with reduced porosity. Procedures are summarized in Fig. 7. Heating rate and final pyrolysis temperature determine the nature of the SiC. High heating rate and low temperature produce amorphous SiC having high porosity while the opposite produces the finely distributed low porosity crystalline SiC. Polymer infiltration is suitable for fabricating complex-shaped and large aerospace components and is characterized with relatively low densification temperature, good control of matrix composition, and ability to produce complex components. In the silicon process, molten silicon at temperature slightly excess of 1415 °C [43] is impregnated on porous carbon fiber/carbon (C/C) composite using capillary pressure or vacuum process to support the infiltration process. During the process, silicon reacts with carbon particles (not fibers) to produce SiC which infiltrate the porous carbon fibers prepreg. Graphitized carbon fibers which are more stable and less reactive with molten silicon than ordinary carbon fibers are used. Other factors to be considered to enhance properties of the carbon fibers/SiC composite from this process are silicon fluidity (viscosity), interaction of molten silicon with carbon fibers (reaction and wettability), and irregular change in silicon volume due to phase change. Recent findings have established addition of Ti_3SiC_2 , Cr_3Si , or SiBC to carbon

Fig. 7 Procedural methods of polymer infiltration



fiber/SiC to fabricate carbon fiber/SiC-Ti₃SiC₂, SiC-Cr₃Si, or SiC-SiBC composites with improved oxidation resistance and fracture toughness. This is achieved by liquid silicon infiltration. Aqueous TiC powder slurry is impregnated on porous carbon fiber/carbon particle (C/C) to produce porous C/C-TiC (20% porosity and density, 1.67 g cm⁻¹) which is infiltrated with molten silicon to obtain C/C-SiC-Ti₃SiC₂ composites having 8% porosity and 2.18 g cm⁻¹ density. In another approach, C/C-TiC-Al is filled with molten silicon to fabricate C/C-SiC-Ti₃SiAlC₂ having improved oxidation resistance [45].

Carbon Fiber Metallic Composites

Most common matrix for fabricating carbon fiber metallic composites is aluminum. Other used metals are magnesium [46], zinc, nickel, cobalt, copper, tin, and titanium [47]. Carbon fibers are incorporated into aluminum to improve its load-bearing

capacities but poor wettability of aluminum and carbon fibers causes difficulty in its manufacturing, thereby limiting its applications [48]. Nevertheless, carbon fiber-aluminum composites are produced by electrodeposition [47], chemical vapor deposition [49], hot forming/pressing [50], and liquid infiltration. Carbon fiber electrodeposition is the coating of carbon fiber gauze with aluminum particles by electrolytic method using ethereal solution containing AlCl_3 , LiAlH_4 in ether at 23 °C and current of 1076.4 Am^{-2} (100 Aft^{-2}) [47]. The carbon fibers gauze used as cathode, on which aluminum is deposited, is produced by filament winding using stainless steel as a mandrel. Before electrodeposition, the mandrel is washed in isopropyl alcohol and dried at 120 °C in an oven to improve the wettability of the carbon fiber. Electrodeposition is carried out in a glove box to prevent contamination of electrolytes with carbon dioxide and water. Anode slime formed during the electrodeposition is removed to prevent its entrapment into aluminum/carbon fiber sheets. Sheets at different orientations are hot pressed to form aluminum/carbon fiber laminates using vacuum heated mold [50]. Nickel using sulfamate (nickel sulfamate, nickel chloride, boric acid) solution at 60–70 °C, pH 3.8–4.2 and current density 8611.2 Am^{-2} (800 Aft^{-2}); 60/40 nickel/cobalt alloy using sulfamate (nickel sulfamate, cobalt sulfamate, boric acid) at 45 °C, pH 3.8–4.2 and current density of 215.28 Am^{-2} (20 Aft^{-2}); bronze; lead; lead-tin alloy and silver are deposited in this way to produce respective carbon fiber metallic composites. Electrodeposition is much simpler and less expensive than chemical vapor deposition but it is limited because of few metals that can be deposited.

Chemical vapor deposition is employed for impregnating aluminum particles from vapor phase on carbon fibers to produce Al/carbon fiber composite powders which are compacted in a die cavity mold and sintered to bulk materials using hot press or used for other purposes. This method uses various carbon fiber as substrates. Typical description of the process involves placing short carbon fiber (150 nm diameter and 10–20 μm long), iodine and aluminum (3 μm) powders in 1:0.1:1 ratio in a quartz tube which is backfilled with argon gas after air evacuation from the front using vacuum pump. The tube is sealed, put in an electric furnace and heated to 500 °C, left at the temperature for 48 hours after which the tube is left to cool to room temperature while inside the furnace. 5% by weight of the aluminum coated carbon fiber are alloyed/mixed with 95% pure aluminum powders in argon atmosphere using planetary mill operating intermittently for alternate 15-min working-rest interval at 200 revolution per minutes for 3 hours to prevent agglomeration/cold welding of the milled powders. Ratio of milling balls to the powder mixture is 10:1 as reported in [51]. The mixture forms the bulk carbon fiber/aluminum by compaction under pressure of 50 MPa and consolidation by heating at 600 °C using spark plasma sintering. In another version of CVD reported in [50], continuous carbon fiber tows are used as substrates on which aluminum (from tris-isobutyl aluminum) is deposited using large rig. Similarly, aluminum-coated coconut shell-based carbon fibers (Al/0.1%carbon) were produced, as reported in [52, 53] using tumbler ball mill operating continuously for 70 hours at 8.5 charge ratio. The composite (Al/0.1% carbon) powders are used as reinforcement for fabricating epoxy composite for bumper application [54, 55]. The powder compaction in a die cavity mold at elevated temperature under pressure to form bulk material is an example of hot forming/

pressing. Forming process (rolling, forging, extrusion) uses deformation by slip or twin in metals shaping to produce semi-finished or finished/wrought product. This approach is used in fabricating aluminum/carbon fiber composite [56] described as deformation bonding. It involves heating aluminum strips to 370 °C and held at 370 °C for 2 hours for structural homogenization and air cooled to the room temperature. Carbon fiber plies are sandwiched between surfaces of two normalized strips after cleaning with acetone and scratching. Then the sandwiched aluminum/carbon fiber composite bonded by cold rolling is subjected to post rolling annealing to alleviate the composites of residual stresses. This method remains an experimental study as its industrial application for fabricating metallic composite has not been found.

Aluminum liquid infiltration is employed in fabricating aluminum carbon fiber composites like liquid silicon infiltration for C/C-SiC composite. Molten aluminum is diffused into porous coated carbon fiber prepreg with the aid of gas pressure or ultrasonic sound vibrations. In the typical production of Al/carbon fiber composite plate, carbon fiber cloth/fabric is placed in a graphitized inner mold, and aluminum is placed in the outside mold, placed over the inner mold. The whole arrangement is placed in a vacuum furnace or the autoclave, where the materials are heated above the melting point of aluminum alloy. Alloy melt is forced into spaces within the fiber fabric under pressure and the autoclave is rapidly cooled by protective cooling gas ventilation [46]. In the rod production, carbon fiber bundles are made to move vertically in melt of aluminum alloy in a heated mold through an elongated entry mold orifice which creates temperature gradient leading to solidification front that prevents melt linkage via the orifice. Pressure is applied from the chamber housing the heated mold to fill the pores within the carbon fiber bundles with the aluminum melt droplets which rapidly solidify while the infiltrated bundles moving through the upper mold orifice are chilled by ventilation from pressurized cooled inert gas. Solidified aluminum infiltrated carbon fiber while cooling moves out of the pressure chamber through the exit orifice to the coiler [57]. In ultrasonic infiltration, carbon fiber from a spool is moved horizontally through preheating and heating furnaces to the composite coiler/take up reel. In the preheating furnace, pyrolytical sizing agent is removed at 700 °C [58]. In the furnace, 1000–10,000 Hz vibration from transducer via ultrasonic horn forces the aluminum melt into pores within the fiber bundles. The transducer is powered by 0.2–5 kW generator [59]. This method is used to produce composite rods (like aluminum/carbon fiber conductor for electricity) and plates.

Carbon Fiber Polymeric Composite

Manufacturing methods for carbon fiber reinforced plastics are hand lay-up, spray-up, bag molding (vacuum bag, pressure bag and autoclave), resin transfer molding (RTM), vacuum infusion/vacuum assisted resin transfer molding (VI/VARTM), compression molding, filament winding, pultrusion, injection molding, extrusion, calendaring and additive manufacturing [60]. All processes can be used for fabricating polymeric composites containing carbon and other fiber. Each of the methods

has proven industrial [61] and experimental research applications. Banana fiber/phenol formaldehyde and carbon fiber cyanate ester were fabricated by RTM. Bisphenol E cyanate ester/carbon nanotube, nanoparticle-carbon fiber/epoxy [62] and graphite nanoplatelet-carbon/epoxy [63] were produced by VI/VARTM. Kenaf/coconut fiber polypropylene [27], carbon fiber polyester [64] and carbon fiber-nano ZrW_2O_8 cyanate ester [65] were fabricated by compression molding. Carbon fiber/cyanate ester was developed using filament winding [61]. Cyanate ester/epoxy resin-carbon fiber was manufactured by hand lay-up/compression molding [66]. Carbon fiber/epoxy was developed using hand lay-up/vacuum bag process. Multiwall carbon nanotubes-carbon fiber/epoxy was manufactured by sonication, hand lay-up and compression molding. Nettle fiber/polymethylmethacrylate was fabricated by direct pouring molding process [23]. Carbon fiber/polyethylene [67] and carbon fiber/poly lactic acid-polycarbonate [7, 8] were produced by single/twin extruders. Also carbon fiber/polypropylene was made using compression molding [22]. Pineapple leaf fiber [68] and banana/polypropylene [69] were developed using compression molding. Also, pultrusion was reported in [70] for producing glass/carbon fiber/polyester composites.

Applications, Properties, and Structure of CFCs

Ceramic matrix composites are used for insulation in crystal growing furnace and as components of vacuum high-temperature industrial furnaces. Their lightweight and low heat capacity allow heating and cooling of the furnace at a high rate, enhancing turnouts at reduced energy cost. Carbon fiber/carbon composites retain their mechanical and wear resistance reputation at elevated temperature, excess of 2000°C much greater than 800°C for alloys due to carbon heat sink feature, making them suitable for rocket nozzle throat insert, thin wall thermal protection structure, metal forging dies, screw fastener, heat sink for electronic component, gear synchronizing clutch, clutch disk, racing car brake disc and aircraft brake disc capable of putting plane to a safe stop from a rejected take-off when its speed is approaching take-off speed and a short runaway distance. Being not wet with molten glass, they are used for fabricating glass-making molds, push-out/ware transfer pads and conveyor guide. Also, they are biocompatible making them suitable for medical implants to replace broken, diseased and ageing bones in humans [12]. Carbon fiber/carbon composites are replaced with C/C-SiC [43], in most of the high-temperature applications due to carbon loss in elevated-temperature oxidation causing wear of the C/C composites. Despite the attractive properties of ceramics composites making them suitable for the applications, their poor tensile properties limit them in applications demanding good tensile properties. Metallic and polymeric composites possess excellent tensile properties though polymeric composites have a relatively least thermal stability but their resistance to chemical attack is better than that of metallic composites. Being light, good conductor of electricity and possessing high strength to weight ratio, aluminum/carbon fiber composites are used for electrical conductor with improved capacity delivery at low cost to replace

heavy steel conductors [5]. Al/carbon fiber composites are used for medium temperature structural member like automobile intake manifolds, transmission housing, wheel suspension, chassis, and body panel; lead, lead-tin, silver, bronze, and copper/carbon fiber composite for bearings and nickel or nickel/cobalt composites for high temperature structural members. Moreover, epoxy/graphite coated with aluminum foil being light and able to withstand dynamic space conditions, is used for communication satellite and other aerospace equipment. Carbon/epoxy composites are used both in military aircraft for wing and fuselage fabrications; passenger aircraft for fairings and undercarriage doors and occupies 40% Eurofighter, 35% F-35 lightning II and 50% Boeing 787 structural mass for tail cone, wing ribs, center wing box, horizontal and vertical tail planes. Other composite used is bismaleimide/carbon fiber. Similarly, aramid, glass, and carbon fiber composite are used for helicopters fuselage and rotor blades with longer service life than metals. Properties of CFCs, the parameters enabling them for various applications depend on composite structures which are functions of fiber orientation/directionality, fiber-matrix interaction, and interfacial adhesion. Since there must be matrix-fiber wettability and no reaction, several techniques are employed to ensure CFC's structural integrity. Coating of porous carbon fiber preform with carbon particles before infiltration prevents deleterious carbon fiber reaction with SiC or Al_2O_3 in C/C-SiC or C/C- Al_2O_3 composites. In aluminum/carbon fiber composites, wetting of molten aluminum with carbon fiber occurs at 1000 °C. Impregnation of the carbon fiber is carried out just above the melting point of aluminum. Deteriorating reaction of carbon fiber with molten aluminum to produce Al_4C_3 above 600 °C is prevented by thermal treatment of the carbon fiber in a vacuum, chemical treatment with K_2ZrF_6 [48], coating the fiber with epoxy-phenolic resin, TiB_2 [58] and using aluminum alloy instead of pure aluminum [46]. Wettability of carbon fiber with polymer molecules is good. Also, porous structure of carbon fiber polymers due to the inability of resin molecules to completely fill in pores within the fiber preform is solved by hot press curing. Sonication of milled carbon fiber or carbon nanotubes in ethanol or acetone before mixing with resin encourages even distribution of the fiber within the polymer and guarantees homogenous structures.

Carbon Nanotubes as a Form of Carbon

The rapid development of nanotechnology and its application in modern information technology depends on the exploitation of new and novel materials, and nanotubes have emerged as promising candidates for this era of nanoscience and hybrid multifunctional nano materials technology. Nanotubes are a product of nanotechnology. This requires precise modification of a material's atoms to suit a particular purpose. A nanotube is a type of material developed to have unique properties arising from their nanoscale dimensions. Nanoscale materials have found applications in colloid science, medical applications, tissue engineering, nanopillars as used in solar cells. The physical, chemical as well as biological characteristics of nanomaterials are greatly affected/determined by its dimensionality, i.e., the surface-to-

volume ratio. The available nanomaterials based on dimensionality are 0D–3D with 2D being used in electronics, medical applications, drug delivery, and biosensor application. Carbon C has an atomic number 6 and is a non-metal essential for a wide range of applications. It can form stable bonds with quite a number of elements which include itself. Graphene, fullerenes, graphite, and graphene are allotropes of carbon. Carbon is a remarkable element showing a variety of stable forms. Under the ambient condition and in bulk form, sp^2 -bonded graphite is the most stable phase of carbon. CNTs are considered prototypes of 1-D nanostructures and have gained attention in harnessing its potential. The invention of nanomaterials has addressed the challenges faced in the use of pre-existing materials. CNTs for example addressed the challenges posed by lithium-ion battery. This innovation seeks to provide services that are cheaper and easier to use. Vehicles that use nanomaterials would use less fuels for operation.

Single-Walled Nanotubes

The SWCNT structure is basically characterized by several items that describe the mechanism of a chiral SWCNT which in turn affects the electrical potential of a nanotube. Chirality is determined by the angle at which a graphite sheet is rolled to form a nanotube. Chirality is often described by using two indices denoted as (n,m) . If $n-m$ is a multiple of 3, a SWCNT behaves like a metal; otherwise, it acts as a semiconductor. Single-walled nanotubes exhibit excellence strength, unique electrical properties, and efficient heat conduction [71].

Double-Walled Carbon Nanotubes

Double wall carbon nanotubes (DWNTs) and multiple wall carbon nanotubes (MWNTs) consist of multiple layers of graphene, which have complex structures (Fig. 1). They can be produced without catalyst and their bulk synthesis is easy. High-purity varieties of DWNTs and MWNTs can be synthesized and produced but cannot be easily twisted. One unique advantage of MWNT lies in the fact that chance of defect is less but once it occurred, it is difficult to be addressed. MWNTs are less accumulation in body. MWCNTs consist of multiple concentric layers of carbon atoms arranged in a tubular structure. The layers are typically between 2 and 50 layers and have varying diameters within the range of 2 to 100 nm. These layers are held together by van der Waals forces allowing some sliding between the layers which contribute to their unique properties. The multiple layers in MWCNTs bring about improved resistance to deformation and fracture; decrease in flexibility, increase in overall conductivity but this also depends on the chirality of the layers.

Properties and Applications of Carbon Nanotubes

CNTs have large surface area to volume ratio which in turn enhances their ability to immobilize biomolecules. This property makes them quite effective for biosensing applications. CNTs have been found applicable in the following areas of biosensing:

- Optical sensors for detecting heavy metals and other pollutants, leveraging their unique optical properties.
- Electrochemical sensors for detecting food contaminants and disease biomarkers. The incorporation of CNTs into these sensors has shown improved sensitivity and faster response times.
- Integration of CNTs into field-effect transistors (FETs) have shown ultra-sensitivity in the detection of viral pathogens. E.g., SARS-CoV-2 which gained attention during the COVID-19 pandemic.

Despite these attractive and fascinating applications, there are challenges faced in the use of CNTs for biosensing applications. These include:

- Integration issue, i.e., the reproducibility and scalability of the material production methods.
- Toxicity concerns.
- Standardization.

Amid these applications, there are recommendations to enhance the performance and widening the applications of CNTs in biosensing applications. Below are some of the recommendations:

- Integration of CNTs with smart materials. These smart materials would respond to environmental changes and enhance the adaptability of biosensors.
- Development of hybrid sensors which is a combination of CNTs with other nanomaterials like graphene to leverage the strength of multiple materials.
- Creation of biosensors capable of detecting multiple targets at the same time which is crucial for applications in medical diagnostics and environmental monitoring.
- Extensive research on biocompatibility and safety.
- Development of wearable biosensors for continuous health monitoring like insulin level in diabetic patients.

Moreover, recent studies have explored and reported the applications of CNTs in improving biogas production and purification processes. Reported applications are discussed below:

- CNTs are used as electrodes to improve microbial activity. This property of improving microbial activity has led to enhancement of biogas production. Addition of CNTs to organic matters can lead to a significant increase in methane

production. Studies have reported an enhancement of 20–30% in biogas yield from organic waste.

- CNTs are also effective in the adsorption of impurities such as CO₂ and H₂S from biogas. Research indicates that functionalized CNTs can significantly improve the adsorption potential for these gases thus enhancing the quality of produced biogas. The use of MWCNTs has been specifically noted for their ability to remove sulfur compounds which are detrimental to biogas quality.
- Studies have also shown that CNTs can be combined with other materials like biochar to produce a hybrid composite material that would enhance both biogas production and purification. These hybrid systems have shown improved performance in aerobic digestion processes. The integration of CNTs into photocatalytic materials has also been explored and demonstrated to have potential for improving the overall efficiency of biogas system.

As much as the benefits of using CNTs in biogas applications are obvious and fascinating, concerns about the impact of nanotube production on the environment have come up. Sustainable sourcing and disposal methods for CNTs need to be addressed to mitigate these concerns. There is also a high initial cost associated with incorporation of nanotubes; however, economic analyses have shown that the long-term benefits of nanotube incorporation like increased biogas yield and quality justify the investment [72].

Conclusions

Properties of environmentally agricultural fiber are studied globally by independent authors, and findings indicate that all environmental fibrous materials are mechanically inferior to the carbon fiber, implying that the carbon fiber retains its position as an inevitable material for composite fabrications. Although many composites for low-performance applications have been developed using agricultural fiber, partial replacement of carbon fiber with environmentally agricultural fiber to produce hybrid composites for high-performance structural applications is recommended. This approach may not only reduce dependence on carbon fiber sourced from nonrenewable resources, having negative impacts on ecology but also add values to agricultural fiber.

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