Synthesis of Carbon Nanofibers and Its Application in Environmental Remediation

Ritu Painuli, Praveen Kumar Yadav, Sapna Raghav, and Dinesh Kumar

Abstract Owing to the inimitable properties of the carbon nanofibers (CNFs), for instance, the enhanced surface-to-volume ratio, nanoscale diameter, physical, mechanical, and chemical properties, they have excellent capabilities in science, biomedicine, energy storage, and environmental science. Carbon fibers prepared from various synthetic techniques have different carbon morphologies and structures. The carbon fibers prepared from electrospinning, chemical vapor deposition with the consequent chemical treatment have flat, mesoporous, and porous surfaces. Along with this, the carbon fibers can be altered with the several materials to expand their application in various fields. Thus, in this chapter, we concentrate on the synthesis and design along with the application of the carbon nanofibers. The synthesis routes of CNFs like chemical vapor deposition (CVD), substrate method, phase separation, electrospinning, etc., have been introduced. In addition, the synthesis of carbon nanocomposites has also been discussed. In addition, the application of the prepared carbon fibers in the various environmental fields has also been explored.

Keywords Carbon fibers · Synthesis · Nanocomposites · Applications

R. Painuli · S. Raghav
Department of Chemistry, Banasthali Vidyapith, Banasthali, Tonk 304022, India
e-mail: ritsjune8.h@gmail.com

S. Raghav
e-mail: sapnaraghav04@gmail.com

P. K. Yadav
Academy of Science and Innovative Research (AcSIR), Chemical and Food BND Group, IRM (BND), CSIR–National Physical Laboratory, New Delhi 110012, India
e-mail: kpraveen.yadav414@gmail.com

D. Kumar (✉)
School of Chemical Sciences, Central University of Gujarat, Gandhinagar, India
e-mail: dinesh.kumar@cug.ac.in

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1 Introduction

In recent years, progress in nanoscience has led to the creation of many nanomaterials (NMs) for sensing applications [76]. Among the various nanomaterial (NM), one-dimensional (1D) materials have gained noteworthy potential [23]. The 1D materials enable short paths for the electrons transfer and encourage electrolyte penetration along the axis of nanofiber [86]. This enhances the sensing application of the nanofibers. Owing to the inimitable optical, electrical, and mechanical properties of CNTs, they have been extensively used for preparing the sensors and biosensors [53]. Besides CNTs, carbon nanofibers (CNFs) have also been widely used or examined because of their unique physical, chemical properties [11, 56]. CNFs possess a high potential for the modification or alteration of surface to form functional hybrid CNF-based NMs which have been utilized in the areas of medicines [71], nanodevices, tissue engineering [1], sensors [38, 50], energy storage [10], and environmental science [52, 66].

CNFs are the filaments present in the nanometer range, organized in graphene layers with a specific alignment parallel to the fiber axis. According to the angle between the growth axis and graphene layers, they are usually classified into three categories, i.e., fishbone, parallel, and platelet. Their arrangement can be found via transmission electron microscopy (TEM). In the CNFs, the regular arrangement among the sheets of a graphene is ~3.4 Å, which is very near to that of graphite diameter, i.e., 0.335 nm. This is the reason that the CNFs are mentioned as graphite nanofibers. The properties of CNFs can be differentiated by seeing the structure derived from the powdered material, the structure of the distinct nanofibers, and the agglomeration of filaments [63]. The difference in the structure of CNFs and CNTs cannot be easily distinguished from the TEM. Under the theoretical definition, nanotubes are synthesized either by the single graphene wrapped in the cylindrical tube, i.e., single-walled CNT or many sheets wrapped together, i.e., multi-walled CNT. In contrast, in CNFs, the graphene layers may not be continuous. In terms of properties, CNTs possess excellent thermal, electrical conductivities, better mechanical resistance, and enhanced structural features. However, the main drawbacks associated with the CNFs are their complex scalability and their excessive cost. CNFs can be divided on the basis of their purpose by concerning the mechanical property necessities and tensile strength and Young's modulus [54]. CNFs are simultaneously categorized as ultrahigh strength and ultrahigh modulus. The CNFs are also classified as super-high strength owing to their high tensile strength. The mechanical properties of carbon fiber can differ even on having an undistinguishable origin and equivalent thickness. Therefore, the main dissimilarity is determined by the arrangement of the fiber. The excellent electrical conductivity of CNFs is of the significant consideration for many applications ranging from electronics to composites. In this chapter, we focus on preparing CNFs by thermal chemical vapor deposition, gas-phase flow catalytic method, spray method, plasma-enhanced chemical vapor deposition, substrate method, electrospinning, phase separation, and templating. The second part explored the preparation of CNFs nanocomposites. In the third part,

various applications of CNFs towards gas sensors, sensors for small molecules, air filtrations, sensors for small molecules, etc., are deliberated. Last, the conclusions and outlooks of the CNFs preparations and its applications are given.

2 Synthesis of Carbon Nanofibers

Owing to the many advantages of CNFs, for instance, enhanced surface area, less density, high specific modulus, excellent strength, good thermal and electrical conductivity, etc, the CNFs have their applications in areas of sensing, adsorbent, electrochemistry, adsorbent, storage, etc. [17, 72]. The following represents the methods that have been used for preparing CNFs. Figure 1 depicts the various methods for preparing CNFs.

2.1 Thermal Chemical Vapor Deposition

For the fabrication of CNFs by the chemical vapor (CVD) deposition method, thermal decomposition of the cost-effective hydrocarbon is carried out over a metal catalyst at a constant temperature of 500–100 °C [82]. According to the fashion by which the catalyst added or present, the CVD method can be categorized into the main types: substrate method and spray method.

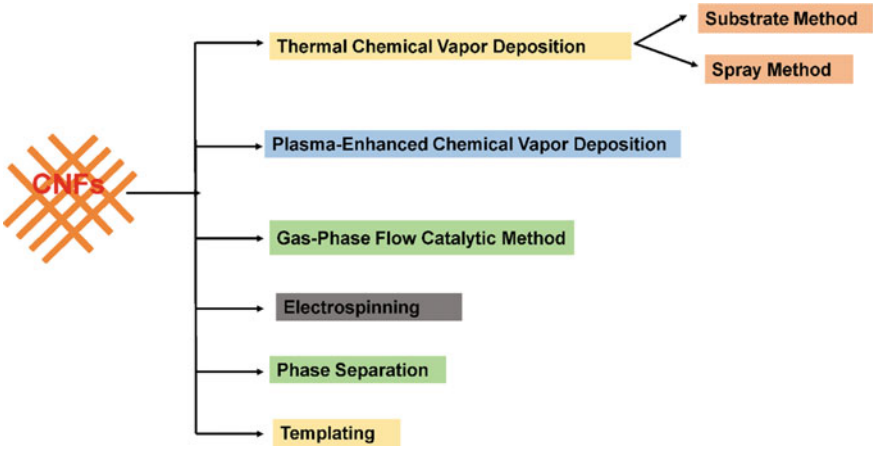

Fig. 1 Various methods for preparing CNFs

2.1.1 Substrate Method

In the substrate method, the SiO_2 fibers or ceramic are utilized as the substrate for the uniform dispersion of the catalyst particles (in their nanosized form) over its surface. At the surface of the catalyst, the H_2 gas is pyrolyzed, then the deposition of the carbon occurs, and further, it is grown to obtain the carbon fibers in the nanoform. Enrique et al. developed high-purity CNFs by using nickel as the catalyst at 599 °C, and for the carbon source, they used $CH_4/C_2H_6/H_2$. Along with the synthesis of CNFs, the effect of various conditions, for instance, temperature, and carbon sources over the layer thickness, porosity, and uniformity of CNFs were also explored [18]. However, by this method, the CNFs are prepared for excellent purity. Since the fabrication of catalyst at the nanoscale is tedious and the product and catalyst cannot be separated in time, therefore it is difficult to obtain large scale production of carbon fibers with this method.

2.1.2 The Spray Method

In this method, the catalyst is mixed with the organic solvent like benzene, and this mixture is sprayed into a reaction chamber with high temperature, to obtain the CNFs. The growth of the carbon fiber, by the spray method, depends on the continuous injection of the catalyst helpful for industrial or large-scale production also [19]. The drawbacks related with this method are the irregular dispersal of the catalyst particles and the difficulty in controlling the ratio of hydrocarbon gases. These issues ultimately lead to the lower production of the CNFs, with a certain amount of carbon black.

2.2 Plasma-Enhanced Chemical Vapor Deposition (PECVD)

Deposition with the help of the plasma is also very important because the plasma possesses high-energy electrons, which offers an activation energy that is required in the CVD process. The electron collision with the gaseous molecules starts the excitation, decomposition, ionization, and compounding of gaseous molecules which produce chemical groups with excellent activity [22, 67]. This method can fabricate the aligned carbon fibers and demands a high cost of production with low production efficacy.

2.3 Gas-Phase Flow Catalytic Method

In this method, the catalyst precursor is heated directly, followed by the introduction into the reaction compartment along with the hydrocarbon gas. The hydrocarbon gas

and the catalyst are decompositions at the two different temperature zones. Then, the catalyst that is decomposed is aggregated into the nanosized particles. Finally, the carbon fibers are synthesized at the nanoscale catalyst particles [8]. Subsequently, the catalyst particles that are decomposed from the organic compound can be disseminated in a 3D space. By using the method, the volatilization quantity can be simply managed. Hence, the amount of fabrication of carbon fibers in less amount of time is enormous, while the uninterrupted fabrication of carbon fibers can be obtained.

2.4 Electrospinning

In the 1930s, a revolutionary technology, i.e., electrospinning technology, was first introduced. It has received widespread attention over the years and has been using for preparing carbon fibers [25, 77]. In this process, a high voltage of static electricity is utilized for charging the polymer solution or melt (Fig. 2). In the presence of an electric field, a Taylor cone is formed by the charged polymers at the spinning port. The former Taylor cone then gets drafted or accelerated. The moving jet is progressively drafted and dispersed. The fibers deposited on the collecting plate are of nanosize because of the fast motion. This results in the formation of the fibrous mat, the same as that of woven fabric. The former fiber matrix is the air oxidized and carbonized in the N_2 environment to attain the carbon fibers.

In comparison to that of other methods available for the manufacturing of carbon fibers, the electrospinning methods possess the following advantages: (I) This method uses high voltages, but the consumption of current is less so that the energy utilization is very less (II) a nanofiber nonwoven fabric can be openly manufactured. The nanofibers formed by this process can be easily made into a nonwoven fabric in the 2D expanded form, as of which, no additional processing is needed after the spinning process. Specifically, the generation of numerous spinning amplified the manufacturing of nanofibers and also upgraded fabrication efficacy, (III) the electrospinning

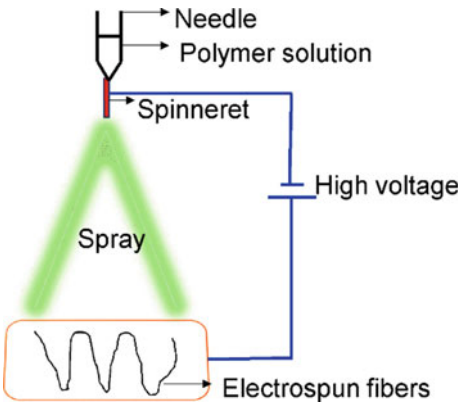

Fig. 2 Schematic representation of electrospinning technique for the synthesis of CNFs

method permits the spinning at room temperature (RT). As a result, a solution to having a low thermal stability compound can also be spun. The raw materials of diverse types have used synthetic polymers, i.e., polyamide, polyester, along with a natural high molecular mass like silk, DNA, collagen for the fabrication of carbon fibers by the electrospinning process.

2.5 Phase Separation

The phase separation is a new technique that comprises gelation, dissolutions, and extraction with the help of various drying, solvent, freezing processes that will lead to the formation of nanoporous foam. Converting the solid polymer into nanoporous foam takes a comparatively long time. The procedure of self-arrangement of randomly dispersed components results in the formation of the systematized assembly or configuration. Local interactions among the constituents themselves cause such an organization. Like that of phase separation, this technique is time–taking in the manufacturing of the continuous polymer nanofibers. Therefore, the electrospinning method is the most proper process for the manufacturing of continuous nanofibers from different polymers [87].

2.6 Templating

The different techniques that have extensively used for the fabrication of nanofibers include drawing, template synthesis, phase separation, and self-assembly [16, 24, 49]. CNFs fabricated by using this template technique are used to make solid or hollow nanofibers of the broad range of raw materials, comprising metals, semiconductors, carbons, electronically conducting polymers, etc. However, the manufacturing of one-by-one continuous nanofiber is not achievable by using this technique of nanofiber synthesis.

3 Preparation of CNF Composites

The complete efficiency of the CNF composites is usually administrated via the dispersion of carbon fibers into a matrix of a polymer. Hence, the role of dispersion is very important in the fabrication of the CNF composites. There are only two methods that govern CNF dispersion in polymer: the sonication process in less viscous solutions and the mixing process. Owing to features like cost-efficacy, straightforwardness, and obtainability, melt mixing method is the most efficiently used method for preparing CNF composites. The methods like a mini–max molder, Haake torque rheometer, and extrusion or roll mill [48, 60] all belong to the method melt mixing,

where a trimmed mixing state is essential for gaining the proper dispersion conditions in the polymer matrix. The high shear mixing will cause a comparatively better CNT dispersion. The aspect ratio governs most of performing the CNF polymer composites. It has been observed that the decreases in the aspect ratio lead to a decrease in the properties of the CNT polymer composites [3]. Thus, an examination of the comparatively less shear mixing technique without the change of the dispersion is still a hurdle in their fabrication via the melt mixing method [47].

The promising method, i.e., the chemical surface treatment, helps the dispersion in the polymer where the compatibility among the polymer matrix and grafting functional group are the chief features that allow the dispersion of CNF and the overall performance of the CNF polymer composites. Usually, the surface of the CNF is treated by soaking it in H_2SO_4/HNO_3 at different temperatures, i.e., followed by the acylation. Then, the functional group adhered to the surface of the carbon fibers via the reaction between the functional groups and the oxidized CNF. By using triamines or diamines as the linker molecules, Li et al. synthesized and characterized the surface-treated CNF [40]. For forming the CNF–C(O)–NH– structure, the amine groups (a bridging compound) links the–NH_2 and CNF. The CNF/ethylene/propylene copolymer composite was synthesized by Kelarakis et al. [32]. The surface of as-prepared CNFs was oxidized by HNO_3/H_2SO_4 and then reduced by sodium borohydride for the formation of the structure of CNF–OH, which was then dispersed in absolute ethanol for forming the CNF–O– structure. In this method, before being mixed in the hardener, the CNFs are dispersed in the liquid epoxy form via sonication. Acetone or different solutions are used to help with the sonication effect. External cooling devices are used to minimize the increasing temperature through the sonication process in most cases. The nanocomposites preparation by the CNF and SC–15 epoxy was demonstrated by Pervin and coworkers [58]. The ultrasonication of SC–15 epoxy and carbon fibers with high intensity was done for performing the mixing process. After the completion of the sonication process, the mixture was filled with hardener, and then the mechanical stirring of high speed was done, followed by the preservation at RT. Choi and coworkers showed the preparation of CNF/nanocomposite [14]. The dispersion of CNF into acetone was carried out via the stirring and sonication process at the RT, followed by the addition of epoxy resin into the CNF acetone solution with continuous stirring and sonication. Then, the mixture is heated to remove the acetone, followed by the addition of the hardener. Finally, it is preserved at RT.

4 Applications

Carbon nanofibers (CNFs) are widely used in various industries such as biomedicine, analytical science, and environmental science because they exhibit exceptional chemical and physical properties. Besides this, these CNFs have a high surface-to-volume

ratio, low defects, high electrical and thermal conductivity, good electron transferability, and easily modifiable surfaces. These properties of CNFs extend its application as sensors for detecting gas, biomolecule, strain, and pressure. CNF–based NMs are in great demand because of their novel characteristics, which make CNF-based NMs potential candidate for various sensing processes [30, 2, 79, 13]. Based on the target materials, CNFs-based NMs applications are as follows.

4.1 Gas Sensors

Li et al. [41] used a solid-phase graphitization method assisted with electrospinning and prepared a one-dimensional CNFs composed of graphitic nanorolls, which act as excellent RT sensors for explosive gases. These CNFs are sensitive to carbon monoxide, methane, hydrogen, and ethanol at RT. They detected carbon monoxide gas at low ppm concentrations [41]. Similarly, Zhang et al. [85] reported ZnO–CNFs composite-based H_2S sensor. The H_2S sensor showed high stability, selectivity, and linear response for H_2S in 50–102 ppm range [85]. In addition, some other workers, Claramunt et al. [15], did similar work for the detection of NH_3. They deposited metal NPs–decorated CNFs on Kapton for the detection of NH_3 [15]. The results showed that by controlling the percentage of Pd and Au, the sensitivity of CNFs to NH_3 could be improved. Moreover, the sensor showed a response time of up to 5 min within a temperature range of 110–120 °C. Moreover, on comparing with the spectroscopic sensors such as quartz-enhanced photoacoustic and mid-infrared sensors [33, 74] which possess the capability of quick detection at RT with no reagent, the operation temperature of Au and Pd NPs decorated CNFs was much higher. To overcome the limitation of the detection temperature, Lee et al. [37] developed a NO_2 gas sensor with a detection limit of 1 ppm. It comprises Wo_3 nanomodule-decorated hybrid carbon nanofibers. This sensor offers a higher sensing surface area. At the material surface, WO^{2+} is associated with the oxygen of NO_2, which helps in the exposure of NO_2 gas at RT [37].

4.2 Strain/Pressure Sensors

A pressure sensor is a device that is used to convert the pressure into an electric signal. This sensor is applied to gases and liquids. Silicon piezoresistive pressure sensor and silicon capacitive pressure sensor that come under the conventional microelectromechanical system (MEMS) have a high potential as sensors because of their several advantages such as they are accurate, power consumption is less, and they are cost-effective. Despite several advantages, they have some limitations and also, for example, they perform poorly in high-intensity piezoresistive measurements. CNFs are also utilized in health monitoring because of their high electrical conductivity, toughness, strain capacity, and low cost [75, 78]. Zhu et al. developed an electrically

conductive polymer nanocomposite using the solvent-assisted casting method that can be utilized as strain sensors with large mechanical deformation. Two elastomers (VM_1, VM_2) with somewhat different compositions have been utilized as the hosting polymer matrix. It is used to manufacture the conductive PNCs strengthened with CNFs. The dielectric performance of the PNCs has been compared. Zhu et al. developed an electrically conductive polymer nanocomposite using the solvent-assisted casting method that can be utilized as strain sensors with large mechanical deformation. Two elastomers (VM1, VM2) with somewhat different compositions have been utilized as the hosting polymer matrix. It is used to manufacture the conductive PNCs strengthened with CNFs. The dielectric performance of the PNCs has been compared. Unique negative permittivity was observed in the composites with the CNF concentration. Additionally, when an extremely large strain is applied, they showed appreciable resistivity, which makes it useful for sensing applications [88]. Similar work was also done by Azhari and coworkers. They also developed a piezoresistive sensor by mixing 1% carbon nanotubes and 15% CNFs. The sensor overcomes the limitation of traditional cement-based sensors and offers more accuracy and reproducibility. The load amplitudes provided by the sensor are up to 30 k, and the gauge factor is 445 [6]. A CNF cement-based composite was developed by Bazea et al. They also found that by adding 2 wt% CNFs to cement, a gauge factor of 190 can be obtained [7]. Hu et al. developed a highly sensitive strain sensor. The sensor is made up of metal (Ag)-coated CNFs and epoxy composites. When they compared the two sensors with and without Ag coating, they found that sensor with Ag coating shows higher strain sensitivity and better conductivity [26]. Tallman et al. by electrical impedance tomography (EIT) studied CNF/polyurethane (PU) nanocomposites for distributed strain sensing and tactile imaging, and for exploring the effect of CNFs filling volume fraction on piezoresistive response. They also revealed that the change in strain was because of a 12.5–15% filling volume fraction [69]. Yan and coworkers developed a flexible strain sensor with the help of carbon/graphene composites nanofiber yarn/thermoplastic polyurethane, with high stability and average gauge factor of >1700 under an applied strain of 2% [78].

4.3 Small Molecules Sensors

CNF-based NMs are widely used in many industries. There use is not limited to strain sensing and for the detection of gas molecules only. They can also be utilized for the detection of small molecules. Huang et al. developed a CNF loaded with palladium nanoparticle (Pd/CNFs) by the combination of two processes. One is electrospinning, and the other is thermal treatment processes. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) studies were done to characterize the nanoparticles. The electrochemical study (CV and EIS) showed that Pd/CNFs have high electron transfer ability and high electric conductivity. The Pd/CNF-modified carbon paste electrode (Pd/CNF–CPE) showed a direct and mediator fewer responses to H_2O_2 and NADH at low potentials. The Pd/CNF–CPE exhibits high sensitivity,

wider linear range response, it is highly reproducible, and these properties make it a suitable and promising candidate for amperometric H_2O_2 or NADH sensor. The sensor was used for the detection of ascorbic acid (AA), uric acid (UA), and dopamine (DA) [29]. The detection limit of Pd/CNFs-based electrodes for DA was 0.2 μM, UA was 0.7 μM, and AA was 15 μM. The linear range was 0.5–160 μM, 2–200 mM, and 0.05–4 mM, respectively. There are many groups of researchers who have worked on Pd NP-loaded CNFs modified carbon paste electrode for sensing different molecules. For example, Liu et al. [43] used a similar electrode for oxalic acid detection with a linear range from 0.2 to 45 nM and a very low detection limit of 0.2 mM. Similarly, Liu et al. by the electrospinning process developed Ni/CNFs composite electrode for the detection of glucose [44]. The electrode is overly sensitive, stable, and catalytically active. The detection limit of the sensor for glucose was 1 μM. Li et al. by one-pot polymerization process synthesized a magnetic composite of Ni NP-loaded CNFs, the neurotransmitter dopamine, laccase. The magnetic composite is high selectivity towards catechol and showed a detection limit of 0.69 μM for catechol and linear range from 1 to 9100 μM [39]. Table 1 represents nanomaterial-assisted CNFs for the detection of small molecules [46].

4.4 Biomacromolecules Sensors

The CNFs have many active sites and high surface area. These properties of CNFs help in protein and enzyme adsorption. The high surface area and numerous active sites of CNFs helps not only in the protein and enzyme adsorption, but CNFs can also provide direct electron transfer and stabilize the enzyme activity [84]. Therefore owing to their wide range of potential, CNFs are the most suitable substrate for the sensor development [59]. Periyaruppan et al. developed a carbon nanofiber-based nanoelectrode arrays for the label-free detection of cardiac troponin–I. The sensor helps in the early detection of the detection of myocardial infarction, a heart disease [57]. The sensor is highly sensitive, which shows the linear response ranges and the detection limit of 0.2 ng/mL. Vamvakaki et al. [73] developed a highly stable electrochemical sensor to protect the protein from the protease attack. They synthesized silica (biomimetically) and encapsulate the CNF-immobilized enzyme acetylcholine esterase to protect it from degradation by thermal denaturation and protease attack. Hence, increase the shelf life of the protein over 3.5 months under continuous polarization. [73]. Arumugam et al. [5] advanced an electrochemical biosensor for the detection of *E. coli* O157:H7. Similarly, Gupta et al. [22] developed a label-free nanoelectrode array based on vertically aligned CNFs for the detection of C–reactive protein with a detection limit of 90 pM. Their study revealed that the concentration of the C–reactive protein causes the increase in charge of transfer resistance as well as a decrease in redox current [22]. Later, Swisher et al. [68] developed an electrochemical biosensor to measure the activity of the protease. This sensor is based on enhanced AC voltammetry using carbon nanofiber nanoelectrode arrays.

Table 1 Nanomaterial-assisted CNFs for the detection of small molecules [36]

Sensor	Detected molecule	Limit of detection	References
CNFs	Trp, Tyr,Cys	0.1 μM	[70]
CNFs	HQ, CC	0.4 μM(HQ), 0.2 μM (CC)	[20]
CNFs	DA	0.08 μM	[51]
Pd–HCNFs	Glucose, H_2O_2	0.03 mM (glucose), 3 μM(H_2O_2)	[31]
PtNP–CNFs	H_2O_2	11 μM	[35]
Pt/CNFs	H_2O_2	0.6 μM	[45]
Pd/CNFs	H_2O_2 and NADH	0.2 μM(H_2O_2)	[28]
Ag–Pt/pCNFs	Dopamine	0.11 μM	[27]
CNF–PtNP	H_2O_2	1.9 μM	[38]
ZNF–CNFs	H_2S	1–10 ppm	[85]
CuCo–CNFs	Glucose	1 μM	[42]
Co_3O_4/CNFs	H_2O_2	0.5 μM	[55]
Wo_3–CNFs	NO_2	1 ppm	[37]
CuO/rGO/CNFs	Glucose	0.1 μM	[80]
Pd–Ni/CNFs	Sugar	7–20 nM	[21]
$Ni(OH)_2$/ECF	glucose	0.1 μM	[12]

CNFs: Carbon nanofibers, Pd–HCNFs: Palladium–helical carbon nanofibers, PtNP–CNFs: Platinum NP-decorated carbon nanofibers, Pt/CNFs: Platinum NP-loaded carbon nanofibers, Pd/CNFs: Palladium NP-loaded carbon nanofibers, Ag–Pt/pCNFs: nanoporous carbon nanofibers decorated with Ag–Pt bimetallic NPs, CNF–PtNP: nanoporous carbon nanofibers decorated with platinum nanoparticles, ZNF–CNFs: Nanoporous carbon nanofibers decorated with platinum nanoparticles, CuCo–CNFs: bimetallic CuCo NPs anchored and embedded in CNFs, Co_3O_4/CNFs: Co_3O_4 nanoparticles on mesoporous carbon nanofibers, Wo_3–CNF: Wo_3 nanomodule-decorated hybrid carbon nanofibers, CuO/rGO/CNFs: CuO nanoneedle/reduced graphene oxide/carbon nanofibers, Pd–Ni/CNFs: Pd–Ni alloy NP/carbon nanofibers composites, $Ni(OH)_2$/ECF: $Ni(OH)_2$ nanoplatelet/electrospun carbon nanofiber hybrids

The enhanced AC voltammetry properties help in measuring the proteolytic cleavage by proteases of the surface-attached tetrapeptides.

4.4.1 Fuel Cell Systems

The fuel cell is an electrochemical cell that acts like a battery that converts the chemical energy say (hydrogen) of the fuel into electricity through a redox reaction [4]. There is an urgent need for technologies which can replace fossil fuel-based systems. There are different fuel cells based on the electrolyte, for example, polymer, alcohol, and alkaline electrolyte-based fuel cells. The alcohol electrolyte-based fuel cell is also known as direct alcohol fuel cells, and if a cell is fed with carbon, then it is called as direct carbon fuel cells [4]. Despite these, some other fuel cell is also available like phosphoric acid, solid oxide [81], and molten carbonate electrolyte-based fuel

cells. The fuel cell can be chosen based on its application, such as durability, temperature, specific energy required, response time, power density, and others. During catalytic reactions in fuel cells, the mesoporous property of CNFs reduces the resistance of inner pore diffusion of products or reactants [9], electrical conductivity, and the metal–support interaction as well. In fuel cell, electrocatalysts are used to increase the rate of reaction. There are many electrocatalysts that are used in a fuel cell. For example, platinum-based electrocatalysts, which are grown on a carbon, shows the ability for energy conversion in the electrochemical process. The support material such as carbon has some property that determines the durability and activity of catalysts. Important criteria of fuel cell electrodes designing are to utilize a high concentration of metal in the catalyst for a certain power ty so that the ohmic drop can be minimized in the catalytic layer. The low surface area (<200 m^2/g) of CNF, which supports for fuel cell catalyst, is a major disadvantage. And because of the low surface area, the proper dispersion of the high number of noble-metal nanoparticles is difficult [34]. The metal deposition method on CNFs looks critical to attaining a good dispersion. Hence, the microemulsion and colloidal methods are more competence to synthesize the Pt catalysts with a smaller size [64]. The carbon fiber support with low surface area is also encouraged to ease the corrosion in fuel cell applications due to the carbon support. Their mesoporous structure also decreases mass transport constraints. Another exciting application of the CNF–supported catalyst is the Pt–Ru catalyst, which is utilized for alcohol oxidation in direct alcohol fuel cells. In comparison with Pt catalysts, this catalyst oxidizes carbon monoxide (CO) at a more negative potential owing to the effect of Ru, which oxidizes CO to CO_2 by the adsorption of oxygen [4]. Sebastián et al. offered different CNFs as the support for Pt–Ru catalysts for the anodic electrochemical reaction of a direct alcohol fuel cell. For example, highly graphitic CNFs as support in Pt–Ru catalyst are utilized, which is suitable for methanol oxidation, while these CNFs exhibit low activity toward the ethanol oxidation. Hence, the importance of pore volume is very high in CNFs because highly porous CNFs can oxidize the ethanol also [65]. Using CNFs in electrodes can expand the performance of the direct alcohol fuel cell owing to many advantages like no parasitic load, operation at RT, operation at a low concentration of methanol, and low catalyst loading in the cathode and anode [83]. The CNF oxidation also signifies a substantial rise in the electro-oxidation of methanol [62]. The maximum support can be attained by balancing three parameters, i.e., an improved metal–support interaction, a sufficient electrochemical surface area, and good methanol diffusion through the catalyst pores [61, 62].

4.5 Air Filtration Applications

The nanofiber membranes have been used in environmental monitoring for air filtration from the old times. As we know the fact that industrialization and globalization are causing a harmful effect on the environment because of which the quality of air has deteriorated in many places, there is an urgent need requiring regeneration

of air through filtration and other processes for better quality filtration media. Air filtration has a wide range of applications; they remove particulate materials from work environments and supply protection from toxic agents. Today, nanomaterials are used as nanofiber mats for air filtration applications. There are several companies that pioneered the use of nanofibers in air filtration. There are several advantages of nanofibers over conventional filtration media. The nanofibers have tiny dimensions and thus offer better efficiency than conventional filtration fibers. In addition, for nanometer-sized fibers, the pressure drop is reduced because of a decrease in drag force on the fiber. The occurrence of slip flow also results in more contaminants passing. The nanofibers have a high surface-to-volume ratio that makes them beneficial to adsorb contaminants from the air and made nanofiber membranes an increasingly popular choice in air filtration applications.

5 Conclusion and Future Perspective

The fabrication routes, along with the environmental application of the CNFs, have been discussed in this chapter. It has been observed that because of the excellent physical, chemical, and optical properties of carbon fibers, they can be utilized in various areas. Owing to the enhanced chemical inertness and mechanical strength, the carbon fiber-based sensors have excellent stability and selectivity to the target molecules. Normally, the carbon fiber structures depend on the shape of the catalytic nanoscale particles that have been used for preparing the CNFs. Usually, CVD and the electrospinning methods have been used for preparing the carbon fibers. As the carbon fibers fabricated from the electrospinning method possess great environmental applications. Other methods, for instance, self-assembly, chemical, hydrothermal methods, and template–based synthesis, could also be considered for preparing the carbon fibers. It is possible to produce carbon fibers based on two-dimensional and three-dimensional scaffolds. By introducing the functional nanosized building blocks in the carbon fibers assembly, more consideration is given in the good design performance energy storage materials, for instance, solar cells, batteries, fuel cell, etc.

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