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Review

Versatile Carbon Nanofiber-Based Sensors

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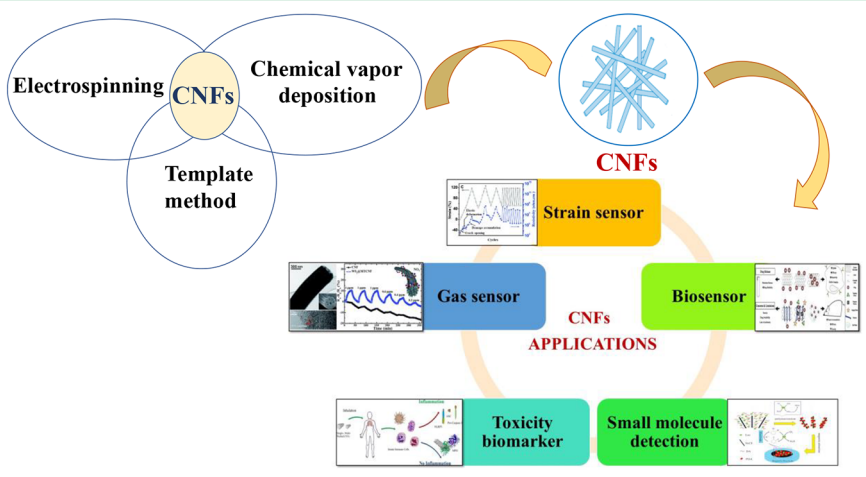

ABSTRACT: Carbon nanofibers (CNFs) display colossal potential in different fields like energy, catalysis, biomedicine, sensing, and environmental science. CNFs have revealed extensive uses in various sensing platforms due to their distinctive structure, properties, function, and accessible surface functionalization capabilities. This review presents insight into various fabrication methods for CNFs like electrospinning, chemical vapor deposition, and template methods with merits and demerits of each technique. Also, we give a brief overview of CNF functionalization. Their unique physical and chemical properties make them promising candidates for the sensor applications. This review offers detailed discussion of sensing applications (strain sensor, biosensor, small molecule detection, food preservative detection, toxicity biomarker detection, and gas sensor). Various sensing applications of CNF like human motion monitoring and energy storage and conversion are discussed in brief. The challenges and obstacles associated with CNFs for futuristic applications are discussed. This review will be helpful for readers to understand the different fabrication methods and explore various applications of the versatile CNFs.

KEYWORDS: *CNFs, sensors, biosensors, toxicity, detection limit*

1. INTRODUCTION

Carbon-based nanomaterials are shining in the field of sensors owing to their unique properties and chemical flexibility. They have prodigious potential in numerous applications, electrochemical supercapacitors,[1] water splitting,[2] photocatalytic applications,[3−5] hydrogen production,[6−8] drug detection,[9−11] pollutant degradation,[5,12−14] sensing,[15−19] optical sensors,[19] battery technology,[20,21] etc. Carbon nanofibers (CNFs), 1D nanomaterials, have a nanometer range diameter.[22] Fishbone, platelet, and parallel[23] structures are the common forms of CNFs based on the angle between graphene layers and the growth axis[24] (Figure 1). In herringbone or fishbone (0° < angle < 90°) structures, graphene layers are stacked obliquely with regard to the fiber axis; in platelet (angle = 90°) structures, graphene layers and the fiber axis are perpendicular; and in parallel (angle = 0°) structures, the growth axis and graphene layers are parallel to each other.[24] Parallel CNFs always exhibit a hollow core (see Figure 1). CNFs show hexagonal carbon arrangements with three sp^2 hybridized carbons having 1.415 Å bond length and a fourth carbon attached via intermolecular stacking with an interlayer spacing of 3.35 Å.[25] The important properties of CNFs include low thermal expansion, light weight, high tensile strength, chemical

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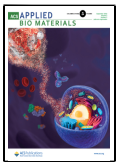

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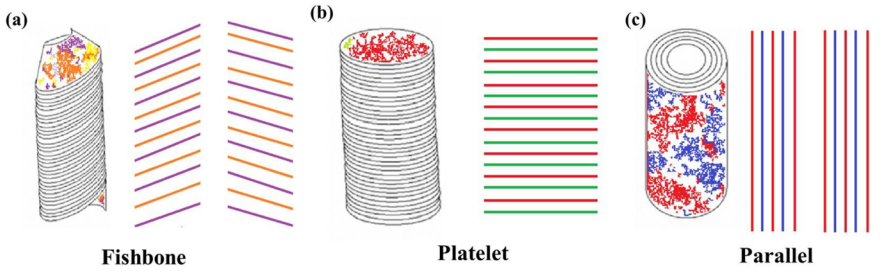

Figure 1. Different forms of CNFs: (a) fishbone, (b) platelet, and (c) parallel.

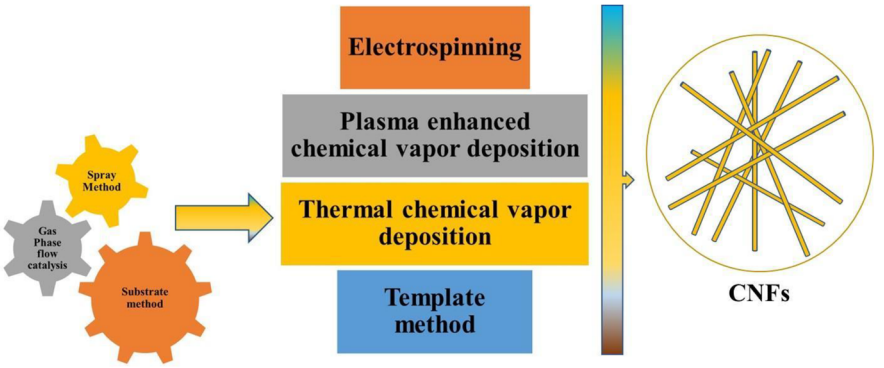

Figure 2. Various techniques for the fabrication of CNFs.

resistance, stiffness, excellent thermal conductivity, and high temperature tolerance.[26] CNFs can be used as catalyst supports because of their favorable characteristics such as large surface area, stability under different reaction conditions, and porosity. They can also be used in fixed-bed applications as CNFs exhibit bulk crushing strength[27] of 1 MPa. Electric conductivity is significant in various applications ranging from electronics to composites. CNFs are organized as sp^2-discontinuous linear filaments with an aspect ratio[28] greater than 100:1, which provides excellent surface area to volume ratio. CNFs can be treated chemically to enhance specific surface area and surface oxygen moieties. Functionalization in an acidic oxidizing medium leads to surface chemistry variation, thus increasing the hydrophilicity in CNFs, which is effective for excellent dispersion in an aqueous medium for carbon particles.[23] There are various routes for the synthesis of CNFs, which include chemical vapor deposition, electrospinning, drawing, templating, and phase separation.[29]

CNFs have edge planes and graphite planes showing great potential for surface modifications to build functional hybrids that find applications as nanodevices,[30] in sensing,[31] in biomedicine, in energy storage,[32] as batteries,[33] as supercapacitors,[34] in energy applications,[35] in fuel cells or solar cells,[36,37] in drug delivery,[37] and in environmental science areas.[38]

This review is organized as follows: Section 1 gives a general introduction to CNFs and their different forms and properties. Section 2 gives insight into various synthesis methods for CNFs, like electrospinning, plasma-enhanced chemical vapor deposition, thermal chemical vapor deposition, and template methods, with the merits and demerits of each technique. Section 3 provides a comprehensive discussion on various sensing applications of CNFs, including strain sensors, biosensors, small molecule detection, food preservative detection, toxicity biomarker detection, disease detection, and gas sensors, and other applications of CNFs like human motion monitoring and energy conversion. Lastly, the challenges and obstacles related to CNFs are given. The detailed review will aid understanding of the broad range of possible usage of CNFs. This review will provide the detailed bibliographic data published by various researchers on sensing applications of CNFs under one roof, which can help readers to understand better.

2. SYNTHESIS OF CARBON NANOFIBERS

CNFs can be synthesized using electrospinning, thermal chemical vapor deposition (spray method, gas-phase flow catalysis, and substrate method), plasma-enhanced chemical vapor deposition, and template methods as shown in Figure 2.

2.1. Electrospinning Technique. Electrospinning is an efficacious method to make polymeric nanofibers because it allows modification of chemical composition, fiber morphology, fibrous architecture, and functionality.[39,40] This technique produces nanofibers ranging in size from a few tens of nanometers to a few micrometers, such as in nonwoven fabrics or mats.[41] The method is simple, less-expensive,[42] and biocompatible[43] and can produce continuous CNFs.[44−46] In this method, the polymer solution is first charged using static electricity (thousands to tens of volts) and in an electric field. Then at the spinning port, the charged polymer tends to form a Taylor cone. The cone is accelerated and drafted as the electric force approaches the spinning mixture tension. The movable jet is thinned and drafted progressively, and fibers are eventually deposited on a collecting plate, creating a fibrous mat close to nonwoven cloth. The fiber mat is then preoxidized in the atmosphere; after that carbonization in a nitrogen atmosphere produces the CNFs. Parameters like concentration, spinning voltage, working distance, and solution feeding rate of the polymer solution are the critical electrospinning processing parameters that can modify the morphology of the fibers formed.[47] For instance, as the

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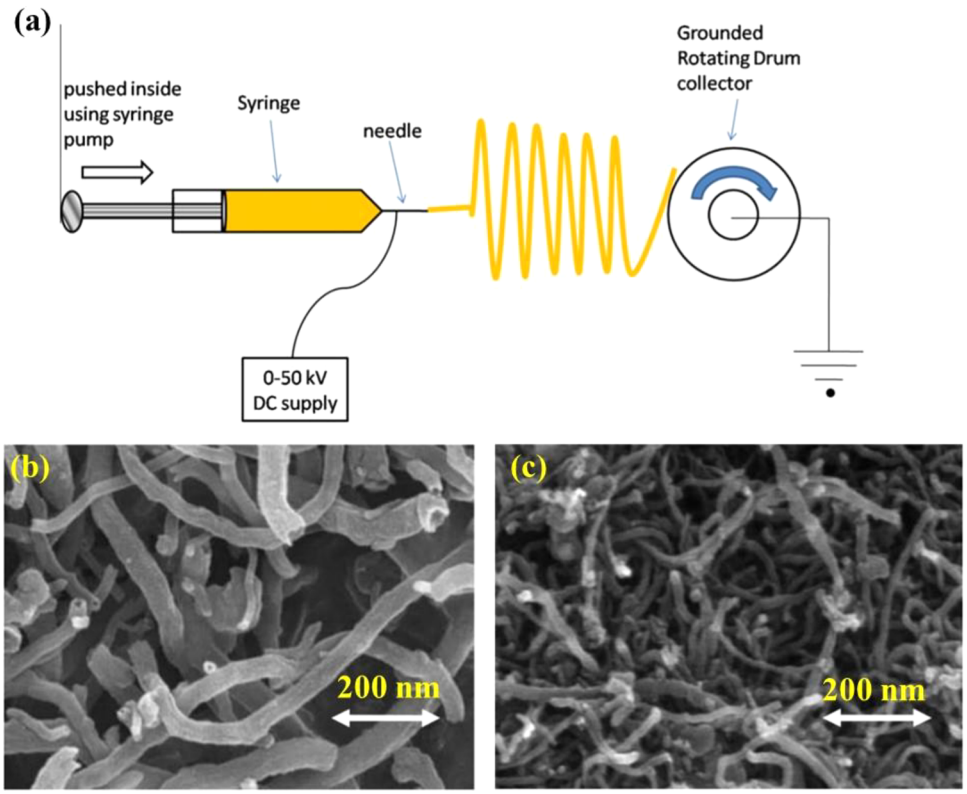

Figure 3. (a) Illustration showing the setup for the electrospinning technique. Reprinted with permission from ref 49. Copyright 2012 Elsevier. (b, c) SEM micrographs of CNFs synthesized by the chemical vapor deposition method. Reproduced from ref 52. Copyright 2008 American Chemical Society.

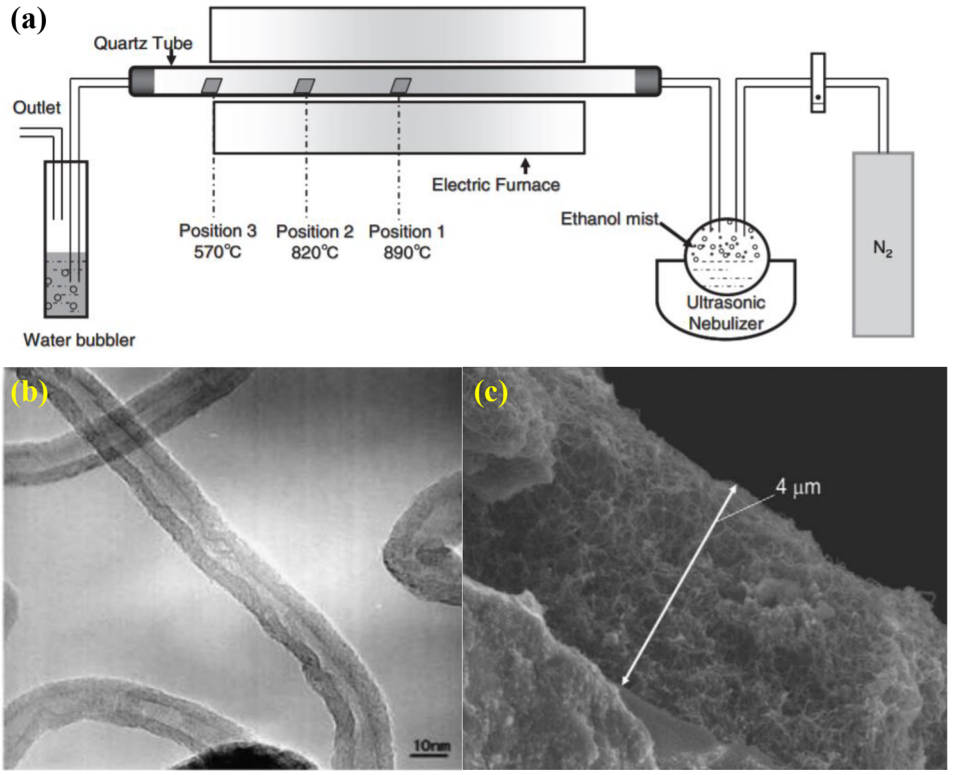

Figure 4. (a) Spray method setup used to produce CNFs, (b) TEM micrograph of CNFs synthesized by gas-phase flow catalysis, and (c) SEM micrograph of CNFs produced on cordierite substrate. Reprinted with permission from refs 55−57. Copyright 2011, 2004, and 2007, respectively, Elsevier).

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carbonization temperature rises, the fiber size shrinks.[48] This method is most effective in synthesizing CNFs (10 nm to 10 μm) with a persistent framework. See the layout of this technique[49] in Figure 3a. The electrospinning method has various benefits; for example, the nanofiber nonwoven fabric can be produced directly, spinning can be done at room temperature, and a wide range of raw materials can be used.[29]

2.2. Thermal Chemical Vapor Deposition. Chemical vapor deposition (CVD) involves thermally decomposing cheap a hydrocarbon composite using a metal catalyst within a temperature range of 500−1000 °C to produce CNFs.[50,51] Hulicova-Jurcakova et al.[52] synthesized graphitic CNFs using the chemical vapor deposition method, the SEM images of which are illustrated in Figure 3b,c. This technique can produce microscale CNFs having a higher aspect ratio. Further classification of this method into the spray method, gas-phase flow catalysis, and the substrate method is done based on the catalyst added. Parameters like high temperature, a vacuum environment, and volatile precursors are required for CVD. Ideal alignment, growth rate, size, and diameter can be achieved using this method.[53]

2.2.1. Spray Method. For the spray method to synthesize CNFs, a catalyst is sprayed in benzene, and the mixture containing the catalyst is then sprayed into a high-temperature reaction chamber. Spray-growing carbon fiber allows continual injection of the catalyst, which creates favorable conditions for the industrial continuous processing.[54] During spraying, the catalytic particles are unevenly distributed and hard to monitor, leading to minute proportions of CNFs, as well as the formation of some carbon black particles. Bao et al.[55] synthesized CNFs using a spray pyrolysis method by placing ethanol in a medication cup. The schematic of the spray method used to synthesize CNFs is shown in Figure 4a.

2.2.2. Gas-Phase Flow Catalysis. This technique explicitly allows catalyst precursor heating and in the form of gas adds it into the chamber with hydrocarbon gas. Hydrocarbon gas and catalyst are decomposed and eventually agglomerated into nanoparticles, which are coated with CNFs.[58] Lim et al.[56] synthesized tubular CNFs (Figure 4b) over a Co−Mo catalyst as support using CO as a carbon source by the gas phase flow catalysis method, leading to continuous production and high yield per unit time as the amount of catalyst volatilization can be regulated in this method.

2.2.3. The Substrate Technique. This process involves SiO_2 fibers or ceramic as a substrate to spread the nanocatalytic particles (transition metals, Ni, Fe, and Co) uniformly on the surface. Hydrocarbon gas pyrolysis onto the catalyst's surface was done, and carbon was deposited to synthesize CNFs. García-Bordejé et al.[57] synthesized high purity CNFs utilizing C_2H_6/H_2 and CH_4/H_2 as the carbon source and catalyst (Ni) on a ceramic substrate at 600 °C. An SEM image of a CNF coating layer produced at 650 °C using cordierite substrate is shown in Figure 4c. The authors also investigated the effect of different temperatures, carbon sources, CNF porosity, uniformity, and layers thickness.[57]

2.3. Plasma-Enhanced CVD. Plasma provides activation energy for CVD as it constitutes a huge number of high-energy electrons (100−300 eV). This method is performed at a lower temperature than the normal CVD method. The collision of a gas-phase molecule with electrons facilitates the gas molecules' decomposition, excitation, compounding, and ionization, thereby producing high-activity chemical groups.[59−61] Saidin et al.[59] synthesized CNFs utilizing the plasma-enhanced CVD (PECVD) method by employing a Ni/Cr-glass thin film catalyst for CNF growth. The influence of the different thicknesses of catalyst and acetylene to gaseous ammonia ratios were investigated, and they concluded that the optimum condition for the synthesis of CNFs is a 1:3 acetylene to NH_3 gas ratio with the width of 15 nm for the Ni/Cr-catalyst. Shoukat and Khan[60] synthesized vertically aligned CNFs by inductively coupled plasma-enhanced CVD using a temperature of ∼650 °C and toluene as a carbon source. Gupta and Sharma[61] studied the effect of N doping on CNF growth by plasma-enhanced CVD and determined that N-doped CNFs had a lower tip diameter, smaller height, and improved field emission characteristics compared to undoped CNFs. Low substrate temperature and high deposition rates are required in this method.[62] Figure 5 shows the experimental setup for the plasma-enhanced CVD method in which reactant gases go into the process chamber via the shower head. Potential is applied to shower head for the generation of plasma.

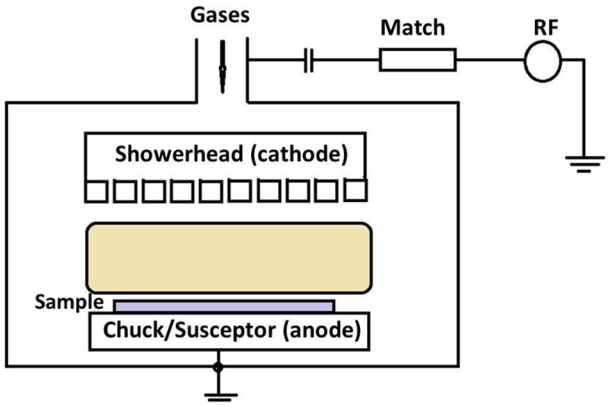

Figure 5. Experimental setup of plasma-enhanced CVD technique.

Aligned CNFs can be produced using plasma-enhanced CVD, but this is an expensive technique having low production efficiency. Parameters influencing the fabrication in this method are RF power, gas flow rates, chamber pressure, temperature, and spacing between the shower head and susceptor. A comparison of synthesis methods for CNFs with merits and demerits is summarized in Table 1.

Table 1. Advantages and Disadvantages of Synthesis Methods for CNFs

Methods	Advantages	Disadvantages
Electrospinning	facile, easy to build, requires high voltage, useful for porous CNFs, effective	requirement for post-treating, carbonization, and high voltage
CVD	high-quality CNFs, excellent conductivity, and efficiency	high cost and high energy consumption
Template synthesis	easy and simple process	removal of template required and expensive
Catalytic hydrogenation and hydrothermal synthesis	high yield	hard to control, high cost, and high energy consumption

2.4. Template Method. This technique is somewhat less prevalent in producing CNFs. The basis for template synthesis of CNFs in this approach is the thermal breakdown of the carbon source in nanosized channels of an anodic aluminum oxide (AAO) film. The film is cleaned to dissolve the AAO leaving the CNFs (Figure 6). Wang et al.[63] synthesized CNFs

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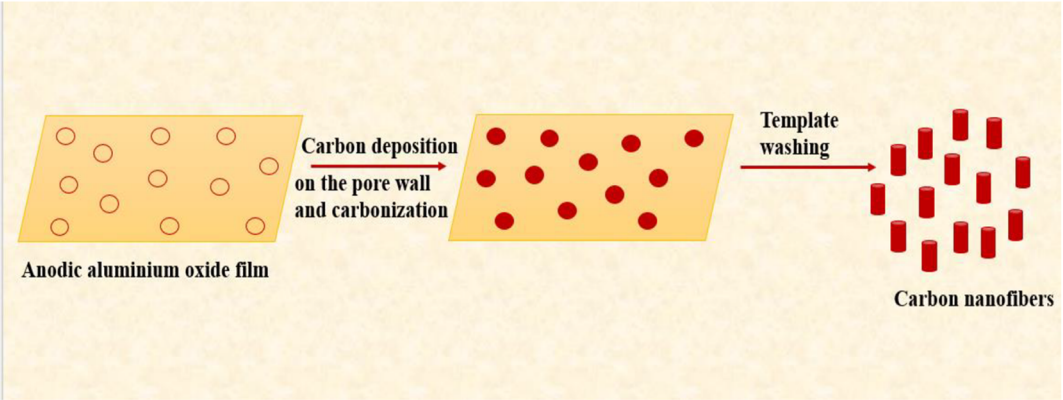

Figure 6. Formation of CNFs by the template method.[23]

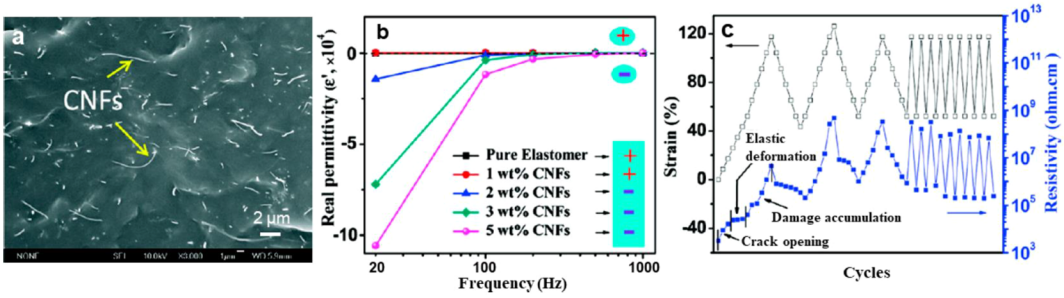

Figure 7. (a) SEM microstructure of the synthesized nanocomposite, (b) real permittivity in 20−1000 Hz frequency range, and (c) instantaneous resistivity response with a strain of 5 wt % CNFs/vistamaxx 6202FL nanocomposite toward cyclic strain. Reprinted with permission from ref 86. Copyright 2011 American Chemical Society.

using Pluronic F127/resol as a precursor in ethanol solvent at the carbonization temperatures between 350 and 700 °C. Thus, synthesized CNFs have nanofibers with linear mesocages having a pore size of ∼18 nm. Xing and co-workers[64] synthesized the mesoporous CNFs using AAO and colloidal silica (porogen) as a film and phenolic resin as a precursor in ethanol at the carbonization temperature of 700 °C. The as-prepared CNFs are mesoporous hollow tubular fibers having a diameter of 21 nm. Processing parameters influencing the synthesis include template wall chemistry, pH scale, concentration, soaking times, and temperature, allowing the nanofibers to be controlled.[65]

Unlike the electrospinning process, CNFs did not shrink during carbonization because of near contact between the nanofiber surface and the pore wall of AAO.[66]

CNFs have also been prepared by other techniques like catalytic hydrogenation[67,68] and hydrothermal synthesis.[69] Chen and co-workers[67] achieved carbon deposition from CO_2 through catalytic hydrogenation using Ni/Al_2O_3 samples containing various potassium (K) concentrations in which K as additive produced the CNFs or carbon deposition during a reverse water−gas shift reaction.[67] Ren et al.[68] used electrolytic conversion to synthesize the CNFs (with diameters of ∼200−300 nm) from atmospheric CO_2 dissolved in the molten carbonates. The authors found that catalytic hydrogenation is a cost-effective method to synthesize CNFs. Gupta et al.[69] synthesized CNFs by the microwave-assisted hydrothermal route using a reaction temperature of 400 °C for 2 h.

2.5. Surface Modification of CNFs. Regulating the CNF surface chemistry is important for knowing their functionality. Both physical and chemical modifications lead to alteration in hydrophobicity, chemical reactivity, and surface charge. Modification was done by surface coating methods (chemical vapor deposition of thin-film coatings, electro- or electroless plating) and chemical functionalization.[70] Surface coating methods enhance the chemical stability and mechanical strength of CNFs and add functionality like variable electrical isolation and conductivity. Chemical functionalization enhances the dispersibility, surface reactivity, and wettability of CNFs. The chemical vapor deposition of thin-film coatings can be done via in situ PECVD coating and surface modification in which catalytic preparation of the carbon nanostructure affects the graphitic structure and condition of the surface of nanofibers.[71] Silicon oxide is the most utilized coating deposited on CNFs through CVD.[72−74] Moon et al. used SiO_x to coat multiwalled carbon nanotubes (MWCNTs) and discovered that the thin layer prevents thermal degradation and high temperature oxidation. It also enhances the field emission properties.[74] Researchers have also coated CNFs and polymers with thin films through CVD[75,76] by electro- or electroless plating. Guillorn et al. used Au electrodeposition for decorating CNFs, validating that the sidewalls and underlying interconnected structures are passivated, and the extreme tips of the nanofibers were electroactive.[77] The chemical functionalization of CNFs permits controlled surface chemistry to allow flexible wettability, both hydrophilicity and hydrophobicity.[78] This can be done by wet etch treatment, plasma treatment, photochemical functionalization, thermal treatment, and adding polymers and linkers.[70]

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3. CARBON NANOFIBER-BASED SENSOR APPLICATIONS

CNFs having large surface areas facilitate the adsorption of a vast number of target molecules. CNFs have a high ability for electron transfer contributing to their extensive range of applications in chemical sensing.[79,80]

3.1. Pressure or Strain Sensors. Traditional pressure sensors like silicon capacitive and silicon piezoresistive pressure sensors have less power consumption and high measurement precision and are economical but are unable to perform well in high-intensity piezoresistive measurements. CNFs are extensively used due to their cheap cost, excellent electrical conductivity, and potentially improved mechanical properties like strain power and fracture toughness.[81−83] CNFs showed exceptional mechanical properties having Youngs' modulus of 25−200 GPa and up to 12 GPa tensile strength.[84] Factors affecting the mechanical properties of CNFs are dispersion and distribution,[85] adhesion and interface, and aspect ratio.[85] Zhu et al.[86] used a solvent-assisted casting process to create a conductive polymer nanocomposite fortified with CNFs using Vistamaxx 6202FL (15 and 85 wt % of ethylene and propylene, respectively) as a hosting polymer matrix material. As shown in Figure 7a,b, CNFs have tremendous mechanical deformation for use as strain sensors. When CNFs are stretched to 120% strain, strain recovery to 40% and resistivity changes of 10^2−10^3 times are observed (Figure 7c).

Yan et al.[83] used carbon/graphene composite nanofiber yarns (CNYs) to synthesize flexible strain sensors that showed brilliant stability and sensitivity. Multineedle electrospinning was used to fabricate CNYs, which were then stabilized and carbonized. When tested under 2% applied strain, the average gauge factor was more than 1700 when the number of substrate and yarns thickness were 129 and 4, respectively. During stretching−relaxation cycles (300), the strain sensor maintained a higher degree of stability. Hu et al.[87] synthesized a resistance-type strain sensor from metal-coated carbon nanofiller/epoxy composites. Multiwalled CNTs and vapor grown carbon fibers (VGCFs) with Ni, Cu, and Ag were utilized as nanofillers. The gauge factor of these sensors having Ag coatings is ∼80 times larger than the gauge factor of a metal-foil strain gauge.

Azhari and Banthia[88] prepared two diverse types of electrically conductive cement-based piezoresistive sensors, one with carbon fibers alone and the other with a hybrid of carbon nanotubes (1%) with CNFs (15%). The latter sensor was repeatable and more accurate than the traditional cement-based sensor having a gauge factor of 445 and a load amplitude of 30 kN.[88] Baeza et al. calculated the properties of strain sensing of the cement composites. The authors synthesized a CNF cementitious composite (CNFCC) and a carbon fiber cement composite (CFCC), which were used as sensors for a conventional reinforced concrete beam. Higher sensitivity was observed with CNFCC with a gauge factor ∼190 when 2 wt % CNFs were added to the cement matrix, and in doing so, the composite sensing ability was increased as the sensor became thinner.[89] Wang et al.[90] used different contents of CNFs with epoxy-based composites to synthesize strain sensors and investigated the effects on different parameters such as gauge factor, linearity, hysteresis, and repeatability. These findings showed that sensors having 0.58 vol % of CNFs had better piezoresistive output than those containing 0.29 vol % CNFs with a gauge factor of 37.1, hysteresis of 6.3%, linearity of 5.5%, and repeatability of 6.3%.[90]

Wu et al.[91] reported a novel and simplistic approach to fabricate a porous polydimethylsiloxane/CNF composite (p-PDMS/CNFs) and used it as a deformable strain sensor. The 3-D porous nanocomposites of CNFs incorporated in PDMS walls had a significantly higher failure strain (∼94%) than PDMS alone (∼48%). The gauge factor of the as-prepared sensor was further modified to offer values between 1.0 and 6.5. The composite exhibited constant piezoresistive output with a quick response time and excellent linearity up to ∼70%. These highly flexible composites have potential as a flexible strain sensor to monitor human joint movements and as conductors that are flexible for wearable electronics because of their tunable sensitivity and conductivity. Recently, Luo et al.[92] developed PDMS/CNF nanocomposites for sensing applications wherein sugar-coated CNFs were used to create the templates, which were then used to fabricate the nanocomposite structures that were tested under cyclic loads at different functional maximum strains, which were used to investigate the piezoresistive sensing functions. Long-term sensor performance was assessed using 12-h durability tests.[92] Chowdhury et al.[93] reported the piezoresistive sensing functions of two different shapes of polydimethylsiloxane (PDMS)/carbon nanofiber (CNF) composites. The compressive sensors of two different shapes, truncated cone and cylinder, were measured with compression strains as low as 3% and gauge factors of 6.3 and 18.3, respectively. The sensing capability of these materials was tested by independently applying strain showing them to be highly repeatable in 1000 cycles under compression. The synthesized nanocomposites were used as sensor arrays to detect pressure from 35 to 690 kPa. The flexibility and ease of the fabrication could overcome the current gap between the performance and applicability of the flexible sensors. Charara et al.[94] synthesized compressible and flexible piezoresistive nanocomposites of CNFs and PDMS for sensing applications. A sugar template was used to synthesize porous PDMS having 74.7% porosity. Due to the conductive CNFs network and the porous microstructures of the fabricated nanocomposites, extremely versatile pressure sensors displayed the piezoresistive characteristics of up to 70% compressive strains. CNFs were used as a conductive nanofillers in a polymer matrix as composites for sensor applications. The commonly used polymers for the matrix are conducting polymers, such as polyacetylene, polypyrrole, polyazulene, polyparaphylene, and polyaniline.[95]

3.2. Biosensors. CNFs have been effectively used in various clinical biosensing applications[29] due to excellent sensitivity to target molecules, high surface area for adsorption, good electron transferability, and strong electrocatalytic oxidation of the small molecules like viruses, nucleic acids, and proteins. Wang et al.[96] fabricated TiO_2/C core−shell nanofiber arrays, which were further doped with Ni−Co nanoparticles, and synthesized composite electrodes that exhibit good stability and enhanced sensitivity (975.3 $\mu A\ \mu M^{-1}\ cm^{-2}$) for glucose determination in the linear range of 1 μM to 7658 μM with a 0.6 μM detection limit; these are a suitable choice as a glucose sensor.[96] Li and co-workers[97] doped carbon nanofibers with different bimetallic MCo (M = Fe, Cu, Mn, and Ni) nanomaterials via electrospinning and thermal treatment that were used to detect glucose non-enzymatically. The CuCo-CNFs showed excellent efficacy for the detection of glucose in human serum samples with good

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reproducibility, excellent stability, high sensitivity (507 μA μM^{-1} cm^{-2}) and a linear range of 0.02 to 11 mM. These composite nanofiber electrodes are suitable replacements for traditional enzymatic glucose estimation tests because they are nonenzymatic and economical because of the presence of CNFs.[97] Similarly, Keerthi et al.[98] used urchin-like CuS and xanthan gum-derived CNFs to produce a sensor for enzyme-free sensing of glucose. The sensitivity of the synthesized composite was as high as 23.7 μA μM^{-1} cm^{-2}. The sensor showed excellent repeatability, durability, and operational stability and a detection limit of 0.03 μM. Glucose oxidase was immobilized onto a Prussian blue functionalized CNF/glassy carbon electrodes to build a glucose biosensor having good stability, repeatability, and selectivity as a glucose biosensor with a quick response of 5 s, linear range of 0.02 to 12 mM, detection limit of 0.5 μM, and high sensitivity[99] of 35.94 μA μM^{-1} cm^{-2}.

Guo and co-workers[100] developed TiC−CNF films via a one-step synthesis technique; these were used to evolve a biosensor for glucose detection that showed sensing performance in a linear range of 0.013−10.5 mM with a lower detection limit of 3.7 μM. TiC−CNFs served as promising substrates for fabricating electrochemical biosensors due to their simple synthetic method and excellent electrochemical efficiency.[100] Liu et al.[101] constructed a highly efficacious nonenzymatic glucose sensor by doping $NiCo_2O_4$ nanoneedle onto electrospun CNFs, which performed over an extensive linear range (0.005−19.175 mM) with a detection limit of 1.5 μM and high sensitivity (1947 μA μM^{-1} cm^{-2}).[101] Recently, Ding et al.[102] used $CuCo_2O_4$ decorated CNFs for enzyme-free glucose detection, and the composite was further treated with electro-polymerization of thiophene-3-boronic acid (TBA) and thiophene. The sensor thus obtained showed higher selectivity of 2932 and 708 μA μM^{-1} cm^{-2} with excellent output with linear range of 0.01−0.5 mM and 0.5−1.5 mM, respectively; in addition, it had excellent stability and repeatability.[102]

CNFs were also used to estimate H_2O_2 as it is a vital biological molecule that has an essential role amid numerous physiological activities; it is a reactive oxygen species, so it plays a role in diabetes, cancer, and neurodegenerative diseases.[103,104] Zhang and co-workers[105] developed a non-enzymatic hydrogen peroxide (H_2O_2) sensor made by carbonization of electrospun polypyrrole nanoparticles embedded in polyacrylonitrile composite nanofibers (NFs). When polypyrrole nanoparticle precursor content was 12 wt %, a significant number of N-doped carbon nanoparticle-embedded carbon nanofibers (NCNPs) were incorporated in the NCNF substrate without any aggregation. The prepared NCNPF composite had a small diameter, high pyrrolic-N content, and higher defective sites, resulting in H_2O_2 reduction with higher electrocatalytic output. NCNPF-12 wt % based H_2O_2 sensor[105] had a quick amperometric response of less than 2 s with 383.9 A M^{-1} cm^{-2} sensitivity. Recently, a novel sensor was designed by Riaz et al.[106] for efficient sensing of H_2O_2 on multiple sensor platforms by carbonizing electrospun PAN fibers having a framework of zeolitic imidazole particles (ZIF-67), which were further doped with carbon encompassing cobalt nanoparticles. When the composite was tested using glassy carbon electrodes (GCEs), it showed sensitivity of 300 μA mM^{-1} cm^{-2} with a limit of detection (10 μM) that was lower than the approved residual limit of H_2O_2 allowed by the US FDA for food packaging applications; however, its linear sensing range was extended up to 50 mM when used as a free-standing film electrode. In addition, when integrated with a portable potentiostat, it allowed mobile detection on screen-printed electrodes (SPEs).[106] Laurila et al.[107] have grown CNFs with Pt particles for the detection of H_2O_2 with a fast response time. CNFs from electrospun PAN were first functionalized using carboxylic acid and HNO_3 treatment before they were used to incorporate hydroxyapatite (HA) or Prussian blue (PB) into FCNF-HA and FCNF-PB composites. The FCNF-HA composite was further coated onto a Au electrode, then cytochrome c was immobilized on the synthesized electrode surface. The fabricated biosensor showed vigorous electrocatalytic activity with a quick response to H_2O_2, having a detection limit of 0.3 μM. The catalytic current was linear (2.0 μM to 8.7 mM) to H_2O_2 concentration.[108]

CNFs have been commonly used to quantify ascorbic acid, uric acid, and particularly levels of dopamine in the human body, which were utilized for an initial diagnosis of Parkinson's disease.[109−111] Recent advances in this field give us a more accurate, rapid, and economical method of initial diagnosis of the disease. Yue et al.[112] fabricated molybdenum disulfide golf ball-like nanosheets deposited onto the CNFs, which were used for the excellent electrochemical dopamine detection in analysis of real urine samples. The as-prepared electrode had a lower detection limit of 36 nM at S/N = 3; their recoveries were shown at different levels of 10, 20, and 40 μM of DA, which was 101.6%, 99.8%, and 107.8% respectively. The synthesized material has outstanding electrochemical properties because of the simultaneous presence of two nanomaterials.[112]

Numerous recent studies have targeted the development of improved biosensors for practical applications in cancer treatment. Afzali et al.[113] fabricated a novel voltammetric sensor for pemetrexed (an anticancer drug) detection utilizing a Pd/CNF/methyl trioctyl ammonium bis-(trifluoromethylsulfonyl) imide ionic liquid modified carbon paste electrode via electrospinning method. The authors demonstrated quasi-reversible behavior of the electrode sensor, and square wave voltammetric (SWV) capacities allowed detection of pemetrexed concentration within a linear range of 1.00−35.0 nM having a detection limit of 0.33 nM under the optimized settings. The designed sensor was used for pemetrexed quantification in human plasma from cancer patients and in pharmaceuticals.[113]

Several types of research have been pursued on the utilization of CNF-based electrodes for the detection of anticancer drugs. For example, a variety of CNF-based electrospun materials were used for detecting nilutamide in prostate cancer treatment.[114] Rajendran et al.[114] established an electrochemical sensor for detection of the anti-prostate-cancer drug nilutamide (NLM) in biological samples (spiked serum and urine samples). The authors prepared N-doped CNFs (N-CNFs) by electrospinning, which were further carbonized, and a solvothermal method was used to grow vanadium tetrasulfide nanorods onto the N-CNFs. A glassy carbon electrode (GCE) was modified with the synthesized material and showed a linear range of 0.001−760 μM with a detection limit of 90 pM, along with fast response and excellent stability.

Kokulnathan et al.[115] used cerium vanadate doped CNFs (CeV/CNFs) for efficacious catalytic activity to detect nilutamide from spiked human urine. A pure glassy carbon electrode was altered using the synthesized composite and displayed an irreversible reduction peak because of nilutamide reduction to hydroxylamine. The material showed a lower

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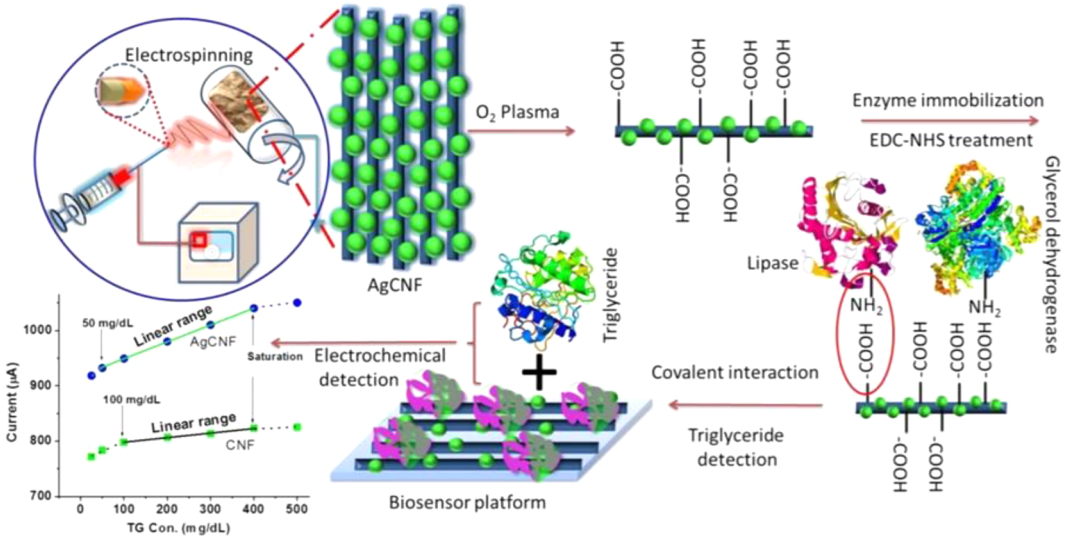

Figure 8. Schematic depiction of the fabrication of CNFs and biosensing for the detection of triglyceride. Reprinted with permission from ref 40. Copyright 2017 Elsevier.

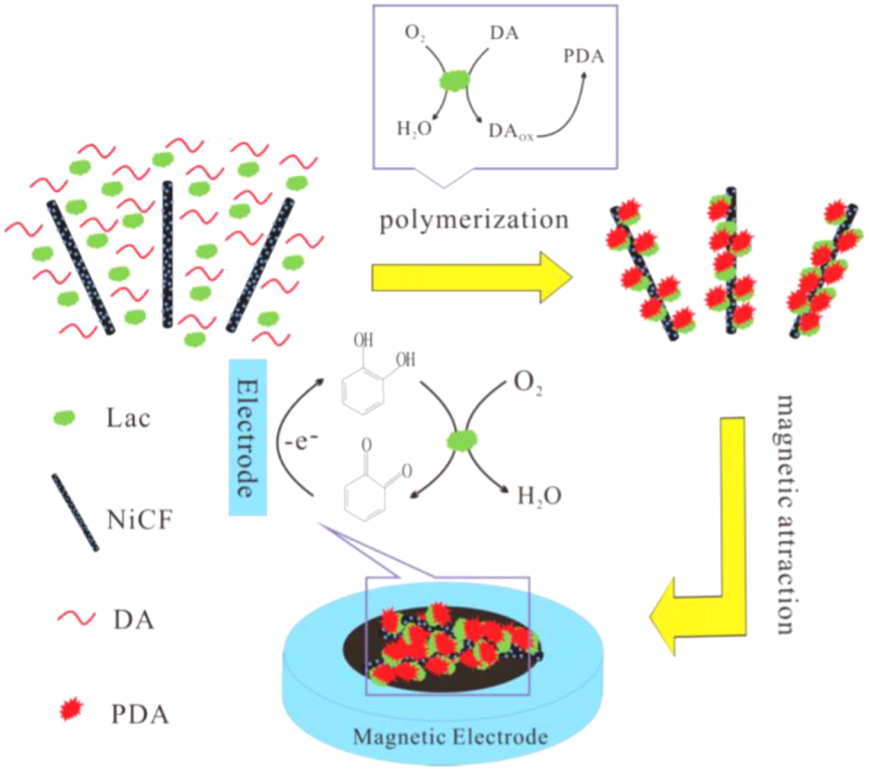

Figure 9. Synthesis scheme of polydopamine−laccase−nickel nanoparticles loaded onto CNFs and sensing application toward catechol. Reprinted with permission from ref 124. Copyright 2014 American Chemical Society.

detection limit of 2.0 nM and higher sensitivity (1.36 μA μM^{-1} cm^{-2}). This method by which drug concentration was precisely mapped in saliva, urine, and plasma is promising. Loaiza et al.[116] fabricated a novel lactate biosensor via chemical reduction of Pt precursor onto a graphitized CNF surface. The developed lactate biosensor displayed a detection limit of 6.9 μM and excellent reproducibility of 4.9%. The biosensor's long-term stability was also assessed, and even after three months of storage at room temperature, 90% of the signal was retained, while retention was 95% after 18 months at −20 °C. These findings have shown that the method can produce responsive electrochemical lactate biosensors with long-term enzymatic activity stability.[116] Recently, Jeong et al.[117] fabricated N-doped CNFs for sensing of cortisol, a hormone regulating glucose level, blood pressure, and carbohydrate metabolism in humans. The synthesized biosensor had a quick response toward cortisol with outstanding sensitivity, reusability, and selectivity with a detection limit as low as 100 aM and linear range of 100 aM to 10 nM.[117] Isoaho et al.[118] developed a promising biosensor for glutamate detection by

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Table 2. Sensing Properties of Different Molecules from CNF-Based Composites

Sensor	Molecule sensed	Linear range	Limit of detection	Ref.
CNFs	dopamine	0.2−700000 μM	0.08 μM	119
CNFs	xanthine	0.03−21.19 μM	20 nM	120
CNFs	tryptophan	0.1−119 μM	0.1 μM	123
	tyrosine	0.2−107 μM		
	cysteine	0.15−64 μM		
CNFs	catechol	1−200 μM	0.2 μM	121
	hydroquinone		0.4 μM	
ZnO/CNFs	dimethyl methylphosphonate	0.1−1000 ppb	0.1 ppb	122
Polydopamine−laccase−nickel NP−CNFs	catechol	1−9100 μM	0.69 μM	124
Co_3O_4−CNFs	H_2O_2	1−2580 μM	0.5 μM	128
CNFs	H_2O_2	1−10 μM	1.3 μM	126
Ag−Pt/CNFs	dopamine	10−500 μM	0.11 μM	110
PdNPs/CNFs-CPE	dopamine	0.5−160 μM	0.2 μM	127
	uric acid	2−200 μM	0.7 μM	
	ascorbic acid	0.05−4 mM	15 μM	
MCNFs	bisphenol A	10^0−10^4 fM	1 fM	129
P-CNFs	carbendazim	0.1−35 μmol L^{-1}	0.038 μmol L^{-1}	130
MoS_2−CNF	vanillin	0.3−135 μM	0.15 μM	131
MoS_2 NSA/CNFs	levodopa	1−60 μM	1 μM	132
	uric acid			
Modified CNFs	Cd (II)	2−100 ppb	0.11 ppb	133
FeCo-CNFs	L-cysteine	1−20 μM	0.15 μM	134
ZnO-CNFs	H_2S	102−50 ppm		135
CoMnZIF@CNFs	α-synuclein	52.6 fM to 0.1 nM	45.7 fM	136
M-CNFs	I_2	5−700 μM	0.59 μM (in PBS)	79
			1.41 μM (in synthetic urine)	

growing CNFs onto a Pt catalyst; detection was done in O_2 containing PBS at −0.15 and 0.6 V vs Ag/AgCl potentials. There were two linear ranges for glutamate when measured amperometrically at −0.15 V vs Ag/AgCl. The first one is between 1 μM and 100 μM with sensitivity of 0.266 μA μM^{-1} cm^{-1} and the second is between 100 μM and 1000 μM with a sensitivity of 0.0208 μA μM^{-1} cm^{-1}. Mondal et al.[40] synthesized a biosensor for triglyceride detection (Figure 8) using electrospinning followed by carbonization and impregnation of Ag NPs in CNFs. The sensitivity of this biosensor (1.232 μA $(mg/dL)^{-1}$ cm^{-2}) was four-times higher than that of CNFs alone (0.33 μA $(mg/dL)^{-1}$ cm^{-2}). Fast response in 10 s along with good selectivity and excellent reproducibility were observed.

3.3. Sensing of Small Molecules. Various studies have used CNF-based materials for small molecule detection. For example, Mao et al.[119] utilized electrospun CNFs for the detection of dopamine, which showed outstanding selectivity, sensitivity, and stability; its LOD was 0.08 μM (S/N ratio 3). Tang et al.[120] used sensitive nonenzymatic CNF-based sensors, which were synthesized via electrospinning and successive thermal treatment, for the detection of xanthine (Xa). A dynamic linear range for xanthine of 0.03−21.9 μM (R = 0.9992) with LOD of 20 nM was found. Guo et al.[121] used electrospun CNF modified carbon paste electrodes for sensing catechol (CC) and hydroquinone (HQ) using cyclic voltammetry and differential pulse voltammetry in real samples of lake water. The results showed that CC and HQ could be detected sensitively and selectively in the presence of 50 μM isomers with a detection limit of 0.2 and 0.4 μM, respectively, and a linear range of 1−200 μM. Lee et al.[122] synthesized hybrid metal oxide composite CNFs by an electrospinning method as a sensor material at room temperature for the detection of dimethyl methyl phosphonate (DMMP). By attachment of a water suspension of CNFs from electrospun polyacrylonitrile (PAN) onto the surface of a carbon paste electrode (CNF-CPE), a CNF-CPE sensor was established by Tang et al.[123] Using constant potential amperometry and cyclic voltammetry, the CNF-CPE electrode could detect the amino acids L-tryptophan (Trp), L-tyrosine (Tyr), and L-cysteine (Cys) without any further treatment. The CNF-CPE showed brilliant electrocatalytic activity and analytical efficiency for amino acid oxidation. Trp, Tyr, and Cys displayed linear ranges of 0.1−119, 0.2−107, and 0.15−64 μM, respectively, with LOD of 0.1 μM (S/N = 3) for all the analytes. In addition, the sensor demonstrated good reproducibility, stability, and selectivity.

Li et al.[124] synthesized a phenolic biosensor by fabricating a composite of polydopamine, laccase, and nickel nanoparticles loaded onto CNFs as shown in Figure 9. NiCNFs are a type of 1-D magnetic material having a large specific surface area and several Ni particles, which could offer ample active sites for laccase immobilization. The fabricated composite was used for sensing of catechol in real water samples with a sensitivity of 25 μA μM^{-1} cm^{-2}. It also exhibited good selectivity and stability having a lower LOD of 0.69 μM (S/N = 3). Table 2 summarizes the properties of CNF-based composites for the detection of several molecules.

Ni et al.[125] synthesized an amperometric nonenzymatic sensor for H_2O_2 detection by doping Co_3O_4 NPs onto CNFs; the resulting sensor was highly selective in the presence of electroactive interferents. Oxidation current was linear over the range of 1 to 2580 μM H_2O_2 concentration, but best was calculated at 0.2 V (vs SCE), which was used to determine H_2O_2 in spiked milk samples. The sensing of H_2O_2 was accomplished by Mao et al.[126] using electrospun CNF webs.

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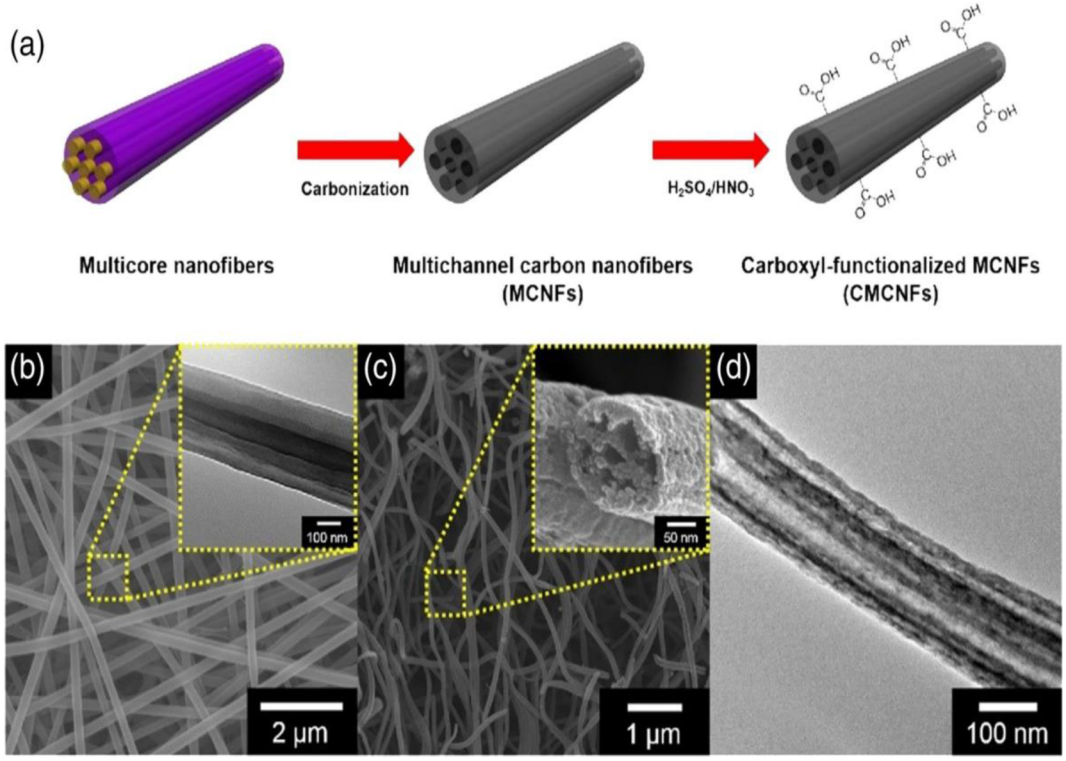

Figure 10. (a) Synthesis scheme for carboxyl-functionalized multichannel CNFs. (b) Multicore NFs are visible through FE-SEM and TEM micrographs. (c) FE-SEM micrographs showing multichannel CNFs. (d) TEM of carboxyl-functionalized multichannel CNFs. Reprinted with permission from ref 129. Copyright 2016 American Chemical Society.

They were made by manipulating the concentration of nanosized graphite domains by changing the carbonization conditions. The response to H_2O_2 concentration was linear in the range of 1−10 μM with sensitivity of 31200 μA mM^{-1}. Wang et al.[127] synthesized Pd nanoparticle loaded CNFs by electrospinning PAN with palladium acetate and then thermally treating to coat a carbon paste electrode (CPE). The PdNP/CNF-CPE demonstrated outstanding electrochemical catalytic activities against dopamine (DA), uric acid (UA), and ascorbic acid (AA) with LOD of DA, AA, and UA of 0.2, 0.7, and 15 μM, respectively. Electrospinning of polyacrylonitrile (PAN) with rhodium acetate accompanied by carbonization yielded RhNP-loaded CNFs (RhNP/CNFs), which were dispersed in DMF using ultrasonic agitation before casting onto the surface of pyrolytic graphite electrodes that were pretreated. The sensor showed excellent electrocatalytic activity against hydrazine oxidation and was used for hydrazine sensing, since it was highly sensitive and selective.

3.4. Detection of Food Preservatives. Bisphenol A is utilized commonly in applications for food packaging, since its structure resembles that of estrogen hormone and it has an endocrine-disrupting impact. Kim et al.[129] developed a transistor sensor, created on aptamer modified multichannel-CNFs, with carboxyl groups on the surface of the CNFs, immobilized on an amine-functionalized electrode (Figure 10). The synthesized sensor showed excellent selectivity and sensitivity toward bisphenol A at a comparatively low concentration (1 fM). The prepared sensor was stable and was reused for repetitive assays.

Cui et al.[130] prepared a 3-D hierarchical helical structure of phosphorus-doped CNFs fabricated by a CVD method and high-pressure annealing, which exhibited a rapid electron transfer. This sensor had high sensitivity and electrocatalytic activity, making it a suitable choice for carbendazim detection in food samples; the LOD was 0.038 μmol L^{-1} (S/N = 3). The sensors' storage stability was also investigated, and only a slight current decrease (∼2.8%) was observed after the electrode was stored for 15 days at room temperature. N-doped CNFs fabricated by nozzle-less electrospinning were used for electrochemical sensing of carbendazim.[137] This sensor has good stability and high sensitivity for the detection of carbendazim in 0.1 mol/L PBS. The studies showed the linear relation with regression equation I_p = 0.891C + 3.37 and a detection limit of 0.053 (S/N = 3). Sundaresan et al. prepared chitosan−CNF composite supported Cu nanoparticles using a sonication approach and used them for an electrochemical sensing platform for carbendazim. The prepared sensor exhibited excellent selectivity with linear range of 0.8−277.0 μM and detection limit of 0.028 μM. They also tested this sensor for analysis of carbendazim in real water washed soil samples.[138]

3.5. Detection of Disease and Toxicity Biomarkers. Periyakaruppan et al. detected ricin, a toxic glycoprotein extracted from castor bean seeds, using aptamer and antibody probes on a nanoelectrode array containing vertically aligned CNFs.[140] The authors also developed a label-free biosensor using a CNF nanoelectrode to detect cardiac troponin-I (cTnI) in the initial evaluation of myocardial infarction.[139] The developed immunosensor showed excellent sensitivity in response to the human-cTnI analyte, detecting it at low concentration (∼0.2 ng/mL), which was 25-times lower than what the traditional methods could detect. It displayed a wide linear range of 0.25−1 and 5−100 mg/mL.[139] Gupta and co-workers[141] designed a CNF-based sensor for the detection of

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C-reactive protein, which acts as a biomarker for cardiac disease; the sensor had a detection limit of ~90 pM.

Phenolic compounds are toxic and can cause cancer and loss of immunity. Li et al.[142] fabricated Ni−Cu nanoparticle-doped CNFs through electrospinning and carbonization. The synthesized composite was mixed with laccase and Nafion to develop a novel sensor. It showed promising electrocatalytic effects for the detection of hydroquinone at 1.5 $\mu A\ \mu M^{-1}$ with a LOD of 90 nM (S/N = 3). The sensor achieved hydroquinone detection in lake water.[142] Yin et al.[143] synthesized a novel phenolic sensor for hydroquinone (HQ), catechol (CC), and resorcinol (RS) detection using Co−Fe selenides doped in a porous CNF modified glassy carbon electrode. The synthesized composite showed 3-D nanostructure, and the electrode showed wide linear ranges and good LOD values of 0.5−200 μM and 0.13 μM, 0.5−190 μM and 0.15 μM, 5−350 μM and 1.36 μM for HQ, CC, and RS, respectively. The synthesized phenolic sensor had excellent stability and selectivity.[143] The ability of the sensor to detect HQ, CC, and RS was also demonstrated by increasing the concentration of the three analytes at the same time. The linearity for HQ, CC, and RS was 0.5−180 μM, 1−160 μM, and 10−120 μM, respectively, with the LOD values of 0.53 (R^2 = 0.998), 0.84 (R^2 = 0.998), and 2.62 (R^2 = 0.995).[143]

3.6. Gas Sensors. Since CNFs are considered to be sensitive to gas exposure, they could be used to make a variety of gas sensors for NO_2,[144,145] NH_3,[145] H_2S,[135] H_2,[146] and C_2H_5OH.[147] The construction of a NO_2 sensor utilizing 2-D WS_2 functionalized multichannel CNFs was proposed by Cha et al.[144] as depicted in Figure 11a. A NO_2 sensor with a 15% response, 4−0.1 ppm concentration range, and gas detection limit of 1 ppm was successfully developed by combining WS_2, a promising gas sensor material, with CNFs. Further investigation of the sensing mechanism using CNFs and WS_2-doped multichannel CNFs revealed that several aspects, including elongated pore channels, high open porosity, and ample gas spots on the edge sites of WS_2, have synergistic effects on enhancing the sensing efficiency (Figure 11b).

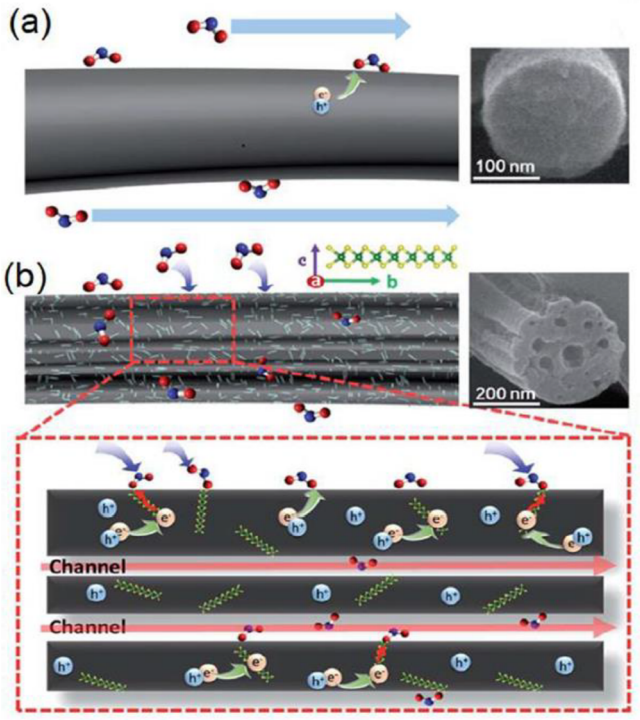

Figure 11. Representation of the sensing process for (a) CNFs and (b) WS_2@MTCNFs for sensing of NO_2. Reprinted with permission from ref 144. Copyright 2017 Royal Society of Chemistry.

H_2S is a flammable and neurotoxic typical atmospheric contaminant for which Zhang and co-workers[135] fabricated a stable sensor with ZnO−CNFs. When compared to pure ZnO nanofibers, the synthesized sensor had an excellent selectivity and response, particularly at 102−50 ppm of H_2S. Furthermore, over 60 days, these sensors showed nearly constant response of ~40−20 ppm of H_2S. The superior performance of the sensors was credited to the carbon protection, which ensured higher ZnO stability, as well as oxygen vacancies, which enhanced its response and selectivity to H_2S.

Wang and co-workers[146] fabricated hierarchical p−n junction nanostructures of SnO_2 nanosheets (n-type) doped onto CNFs (p-type) by the combination of electrospinning and hydrothermal methods. The efficacy for gas sensing of the hierarchical nanostructured material with hydrogen as a target molecule was investigated. Due to the synergistic effect between SnO_2 nanosheets, CNFs, and the sensor, the predicted sensing outputs (large response, low operating temperature, and quick response recovery behavior) were achieved; in 100 ppm of H_2, the gas sensor had a ~4 s response time and less than 16 s recovery time.[146]

Yan and Wu[147] synthesized Sn-SnO_2/carbon heterostructure NFs using electrospinning and heat treatment and used them for selective sensing of C_2H_5OH; the heterostructured fibers showed enhanced sensing efficacy compared to pure SnO_2, along with a linear dependence of response on the C_2H_5OH concentration (10−100 ppm) with brilliant selectivity and recovery due to high surface area and pore structures offered by the 1-D CNFs as well as the unique sensing mechanism by the hybrid Sn-SnO_2/CNFs.[147] Lee et al.[148] fabricated WO_3 nanonodule-CNFs employing single nozzle co-electrospinning for the detection of NO_2. The composite had a larger sensing surface area (147−276 $m^2\ g^{-1}$), and WO^{2+} on the material's surface combined with O_2 of NO_2, thereby allowing NO_2 detection at room temperature (rt) within a detection limit of 1 ppm. Monereo et al.[145] studied the application of self-heating effects in larger arrays of randomly focused CNFs for gas sensors for NO_2 and NH_3. Similarly, Claramunt et al.[149] used CNFs decorated with metal NPs on Kapton for NH_3 detection.

3.7. Human Locomotion Monitoring. Persistent human motion tracking with the help of CNFs can help physicians and therapists build tailored treatment programs for individuals suffering from disorders like multiple sclerosis, Parkinson's disease, and strokes. Sengupta et al.[150] prepared a stitchable, wearable carbon nanofiber−polydimethylsiloxane (CNFs-PDMS) based piezoelectric sensor. The developed sensor exhibited force sensitivity of ~1.82 kN^{-1} with a linear response measured through electromechanical tactile sensing for a normal force up to 20 N. The functionality of the as-prepared sensor was tested through gesture monitoring and human motion detection via different experiments of wrist movement, walking, and jogging. Lu et al.[151] prepared a PAN-based CNF and carbon black sensor for the detection of human motion. These sensors exhibited a linear range of 0.1−20%, could detect small strain of 0.1%, and showed a strain sensing maximum of 100%. Furthermore, quick response time (67 ms) and exceptional long-term durability (continuous stretching

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time of 7500 s) showed that the film sensor was capable of detecting human motion in real time. Cheng and co-workers[152] fabricated a compressible and stretchable hydrogel strain sensor using CNF powder and poly(vinyl alcohol) (PVA) by freezing−thawing cycles. The sensor exhibited low plastic deformation (10%) and little energy loss efficiency of 5.62% and 12.13% for stretching and compressing, respectively. The authors used it for detecting multiple stretching behaviors of humans like joint bending, breathing, or swallowing.

3.8. Energy Applications. Advanced energy conversion and storage systems such as supercapacitors and lithium-ion batteries are urgently needed to meet energy needs and to support new applications like electric vehicles and portable electronics. CNFs can be used in supercapacitors owing to their high specific surface area. For supercapacitor applications, a new porous electrode material (graphene-doped CNFs) was utilized by Zhou and Wu.[153] They prepared a supercapacitor by electrospinning and carbonization method. In 6 M KOH, the developed material showed specific capacitance of 263.7 F/g and cycling stability for energy storage with 86.9% retention ratio. Kim et al.[154] used a mesoporous CNF web for high-performance supercapacitor applications. The developed carbonized fiber showed a high surface area of ∼500 m^2 g^{-1}. The observed specific capacitance was 128 F/g along with energy density of 16.0−21.4 Wh kg^{-1} and 75.0−58.2 Wh kg^{-1} in aqueous and organic electrolyte, respectively. Jung et al.[155] used CNFs for supercapacitors prepared from poly(acrylonitrile-*co*-vinylimidazole) via electrospinning and thermal treatment. The capacitor showed specific capacitance ranging between 122 F/g and 86 F/g; power density and maximum energy were calculated from the Ragone plot and were 7.2 kW/kg and 47.4 Wh/kg, respectively. Lithium-ion batteries are effective power sources for electronic devices. CNFs are excellent anode and cathode materials to use in lithium-ion batteries. Zeng et al.[156] prepared N-doped CNF−Si/C composites by carbonization and electrospinning technique. The developed composite increased the electrochemical properties of lithium-ion battery anodes. At 0.2 A/g, it showed reversible capacity of 945.5 mAh g^{-1} with 64% capacity retention for 150 cycles, and at 0.5 A/g, it showed reversible capacity of 538.6 mAh g^{-1} for 500 cycles. $LiMn_2O_4$@C/CNFs were used as a cathode material in lithium ion batteries with electrochemical performance of 126 mAh g^{-1} at 0.2 C at a capacity of 92 mAh g^{-1} after 1000 cycles[157] at 1 C. Other researchers have also used CNFs for applications in lithium-ion batteries.[20,158,159]

4. CHALLENGES AND OBSTACLES FOR CARBON NANOFIBERS

Despite the positive outcomes derived from using CNFs as a sensor, future risks must be addressed. CNFs are indeed promising in biomedical applications as biosensors. Still, limited information on CNF toxicity, cytocompatibility, and dispersibility has been the foremost hurdle preventing them from being used as effective biomaterials or for clinical applications. Major challenges with CNFs are the dispersion of the composite in the matrix material, orientation and alignment, interface, and densification of the composite processing.[160] Inhalation toxicity was the focus of the majority of toxicity studies. They have the unique capacity for inducing proliferation of mesenchymal cells, granuloma formation, and fibrogenesis.[161] However, surface area, chemical structure, purity, agglomeration propensity, and functionalization are some of the factors that can influence and regulate CNF toxicity. Furthermore, the concentration of CNFs utilized in toxicity studies is commonly specified in μg/mL, which is considerably higher than the actual concentrations used in clinical settings. Thereby toxicity levels get unreasonably high.

Studies have shown that CNFs with nonfunctionalized hydrophobic composition and heavy metal impurities are more cytotoxic,[162] while many researchers have a different opinion concerning the functionalization of the CNFs with carbonyl, hydroxyl, or carboxyl groups that can result in higher toxicity than the unfunctionalized ones.[163] Larger physical sizes (length, diameter) have led to increased cytotoxicity compared to thinner and smaller materials.[164] To obtain unswerving toxicity results of CNFs, in-depth investigation and protocols are urgently needed to integrate research efforts on safety, administration evaluations, and exposure.

5. CONCLUSION AND FUTURE PERSPECTIVE

Based on the facts discussed here on the CNF-based materials, it can be visualized that they play a vital part in fabricating different types of sensors for various applications. The different synthesis routes along with challenges and obstacles of CNFs have been emphasized. Among all, electrospinning is the most prevalent route for synthesizing CNFs. Heteroatom-doping of CNFs with other materials, such as metals, nitrogen, nanoparticles, or polymers, has improved the sensing efficacy. The overall success of such studies has immense consequences for fundamental science, technological explorations, and further tailoring of CNFs. The high aspect ratio and large surface area facilitate adsorption of a vast number of target molecules. More active sites facilitate high electron transfer contributing to their extensive range of applications in chemical sensing. This work comprehensively reviewed the considerable role of CNFs in various sensing applications.

More efforts and focus should be put into uncovering and exploring the possible benefits of implementing CNFs. Finally, the lack of validated data on CNF toxicity should prompt researchers to compile the data set needed for risk assessment. For example, standard tests and chronic animal bioassays may be used to carefully mimic real-world situations for systemic, local, and occupational implementation of CNFs.

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Notes

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