

Carbon Nanofibers for Sustainable Nanotechnology: Synthesis, Functionalization, and Applications in Energy, Catalysis, Environmental Remediation, and Biomedicine

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Abstract

Carbon nanofibers (CNFs) are a versatile family of one-dimensional (1D) sp^2/sp^3 -hybridized carbonaceous nanomaterials with high aspect ratios, impressive electrical conductivity, mechanical strength, tunable surface chemistry and interconnected porous structures. As the world's manufacturing paradigm is shifting toward sustainable approaches, CNFs have become core building blocks in renewable energy conversion, electrocatalytic transformations, environmental remediation and nanomedicine. The review presents a comprehensive analysis of CNF production and functionalization linking green precursor engineering to the performance in a wide range of applications. First, the major synthetic routes are scrutinized with special emphasis on the lignocellulosic and waste-derived sustainable carbon precursors. The major synthetic routes include catalytic chemical vapor deposition (CCVD) and polymeric/biomass-based electrospinning followed by oxidative stabilization and carbonization. Then, the surface modification paradigms with physical/chemical pore activation, heteroatom doping (N, P, S, and B), and interfacial hybridization with transition metal/metal oxide nanoclusters are evaluated. We systematically review the functional efficiency of engineered CNF matrices in electrochemical power storage (supercapacitors, rechargeable metal-ion batteries), electrocatalytic mechanisms (oxygen reduction, hydrogen evolution and oxygen evolution reactions), environmental decontamination (adsorptive capture of radionuclides and heavy metals, membrane separation and advanced oxidation) and biomedical platforms (biosensors, drug delivery and tissue scaffolds). Finally, the paper critically discusses life-cycle sustainability, green metrics, bottlenecks for technology scale-up and emerging translational challenges.

Keywords: Carbon nanofibers; Sustainable nanotechnology; Green synthesis; Surface functionalization; Energy storage and catalysis; Environmental and biomedical applications.

1. Introduction

The current trend toward circular and carbon neutral technologies has triggered a considerable amount of research on nanostructured carbon allotropes. Carbon nanofibers (CNFs) are in a unique position among zero-dimensional (0D) fullerenes, one-dimensional (1D) carbon nanotubes (CNTs), and two-dimensional (2D) graphene. CNFs are cylindrical or conical nanostructures, composed of stacked, rolled or nested graphene layers (usually in “cup-stacked,” “herringbone,” or “platelet” orientations) with diameters typically in the range 50-1000 nm and lengths ranging from micrometers to centimeters [1], [2].

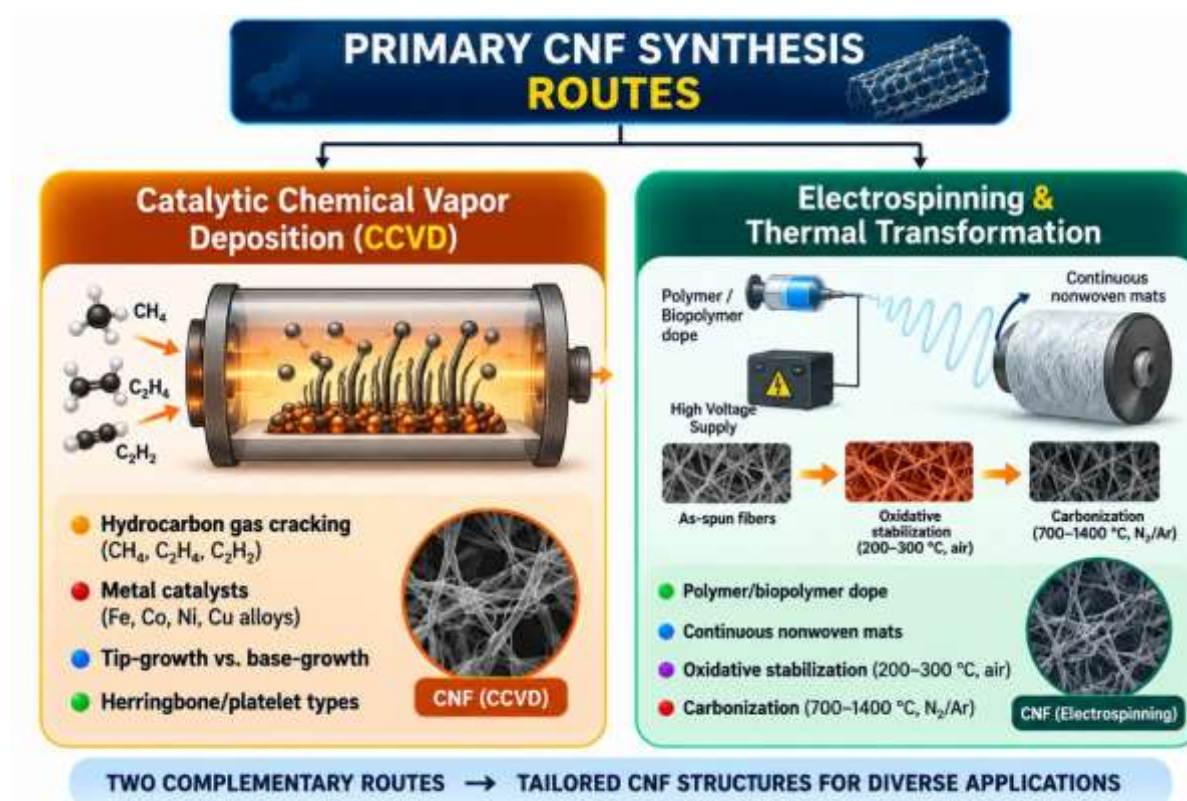
CNFs are different from single- or multi-walled carbon nanotubes in that they have an edge-plane-rich exposed surface, excellent percolation network formation abilities and high chemical functionalizability [3]. Typical problems with

carbon nanotubes include high synthetic cost, restricted inner pore access and strong bundling tendencies. Traditionally, synthetic methods were based on high temperature catalytic chemical vapor deposition (CCVD) using petroleum gasses or on electrospinning synthetic precursors such as polyacrylonitrile (PAN) and pitch [1], [3]. Instead, the current materials chemistry paradigm imposes a sustainability imperative, favoring the use of renewable precursors (e.g., lignin, cellulose, and bio-tar) in combination with energy-efficient activation and functionalization protocols [4], [5].

This review covers the synthetic chemistry, surface engineering and broad technological applications of CNFs. We investigate the role of controlled pyrolytic chemistry and functionalization protocols in controlling the morphological, structural, and electronic properties, leading to high-performance integration in the energy devices, catalytic reactors, wastewater treatment units, and advanced biomedical platforms domain.

2. Synthesis Methodologies of Carbon Nanofibers

The primary bottom-up and top-down methodologies for synthesizing CNFs dictate their structural ordering, graphitic crystallite dimensions, defect densities, and porosity profiles.



2.1 Catalytic Chemical Vapor Deposition (CCVD)

CCVD relies on the transition-metal-catalyzed thermal cracking of volatile hydrocarbons (e.g., CH_4 , C_2H_4 , C_2H_2) or carbon monoxide over active metal nanoparticles (principally Ni, Fe, Co, and their binary alloys such as Ni-Cu or Fe-Cu) supported on refractory oxides like Al_2O_3 , SiO_2 or carbon textiles [6], [7]. The process operates through three coupled physical stages:

1. **Adsorption and Dissociative Chemisorption:** Hydrocarbon molecules impinge on active crystallographic facets of the catalyst nanoparticle and catalytically dehydrogenate.
2. **Bulk and Surface Carbon Diffusion:** Elemental carbon dissolves into the catalyst lattice and diffuses driven by thermal and concentration gradients across the nanoparticle.
3. **Crystallization and Extrusion:** Carbon supersaturates and precipitates on preferred low-energy crystallographic faces, extruding continuous fibrous graphitic sheets.

Depending on the interfacial adhesion energy between the catalyst nanoparticle and the underlying substrate, two classical growth modes emerge:

- **Base-growth:** Strong metal-support interaction anchors the particle to the substrate while the nanofiber extends upward.
- **Tip-growth:** Weak interaction permits the precipitating carbon filament to lift the catalyst nanoparticle, positioning it at the terminal apex of the growing nanofiber [6].

The resulting graphene layer orientations—classified as *platelet* (layers oriented perpendicular to the fiber axis), *herringbone* (layers tilted at an angle, exposing extensive basal and edge planes), or *tubular*—are governed by catalyst geometry, operating temperature (550–1000 °C), and gas feed velocity [6], [7].

2.2 Electrospinning and Thermochemical Conversion

Electrospinning has emerged as a versatile, scalable approach for yielding free-standing, continuous nonwoven CNF mats with tunable fiber diameters and interconnected porous architectures [1], [2]. A viscous polymer precursor solution is charged to a high electrical potential (typically 10–30 kV). When electrostatic repulsion overcomes surface tension, a charged liquid jet erupts from the Taylor cone, experiences rapid whipping instabilities and solvent evaporation, and deposits as continuous ultrafine fibrous sheets [2], [8].

Converting as-spun polymeric precursor mats into conductive CNFs requires a multi-stage thermal protocol:

Oxidative Stabilization

Conducted in an air atmosphere at 200–300°C at slow heating rates (0.5–2 °C min⁻¹). For standard polyacrylonitrile (PAN), stabilization triggers:

- Cyclization of neighboring nitrile ($-C\equiv N$) groups into conjugated ladder-like hexahydropyridine rings;
- Dehydrogenation generating carbon-carbon and carbon-nitrogen double bonds;
- Oxidative crosslinking, which prevents melting or fiber fusion during subsequent carbonization [2], [3].

High-Temperature Carbonization

Conducted in an inert atmosphere (N₂, Ar, or vacuum) at 700–1400 °C (and graphitized above 2000 °C when high crystallite ordering is required). During this process, non-carbon heteroatoms (H, O, N) are pyrolyzed as volatile species (H₂O, HCN, NH₃, CO, CO₂), leaving an integrated turbostratic carbon framework composed of aromatic graphene domains [2], [3]. The carbon yield, fiber shrinkage, Brunauer–Emmett–Teller (BET) specific surface area, and I_D/I_G Raman ratio (ratio of defect-induced D-band to graphitic G-band) vary directly with the terminal carbonization temperature [2].

2.3 Biomass and Sustainable Precursors

To eliminate reliance on petroleum-derived, toxic, and expensive PAN polymers, green chemistry research has turned toward bio-renewable polymers [4], [5]:

- **Lignin:** A major aromatic byproduct of the pulp and paper industry and bioethanol refining. Due to its high carbon content (>60%) and crosslinked polyphenol structure, lignin is an attractive precursor [4]. Because technical lignins often display low chain entanglement, they are typically blended with spin-aids (such as low concentrations of polyethylene oxide [PEO] or polyvinyl alcohol [PVA]) to facilitate continuous fiber formation prior to stabilization and carbonization [4].
- **Cellulose and Nanocellulose:** Cellulose acetate, bacterial cellulose, and TEMPO-oxidized cellulose nanofibrils (CNFs) serve as sustainable carbohydrate backbones that convert into carbonaceous matrices under controlled catalytic dehydration and pyrolysis [5].

- **Biomass Tars and Food Waste:** Gasification tars, agricultural residues, and chitosan derived from seafood processing waste have been electrospun or hydrothermally carbonized into CNF architectures, combining waste upcycling with green manufacturing [5].

3. Surface Engineering, Heteroatom Doping, and Nanocomposite Architectures

Pristine carbon nanofibers, while mechanically robust and electrically conductive, often possess relatively low pristine specific surface areas (typically 20–80 m² g⁻¹) and hydrophobic, chemically inert graphitic basal surfaces [2], [8]. Surface engineering routes are therefore applied to optimize electrochemical, catalytic, and adsorptive performance.

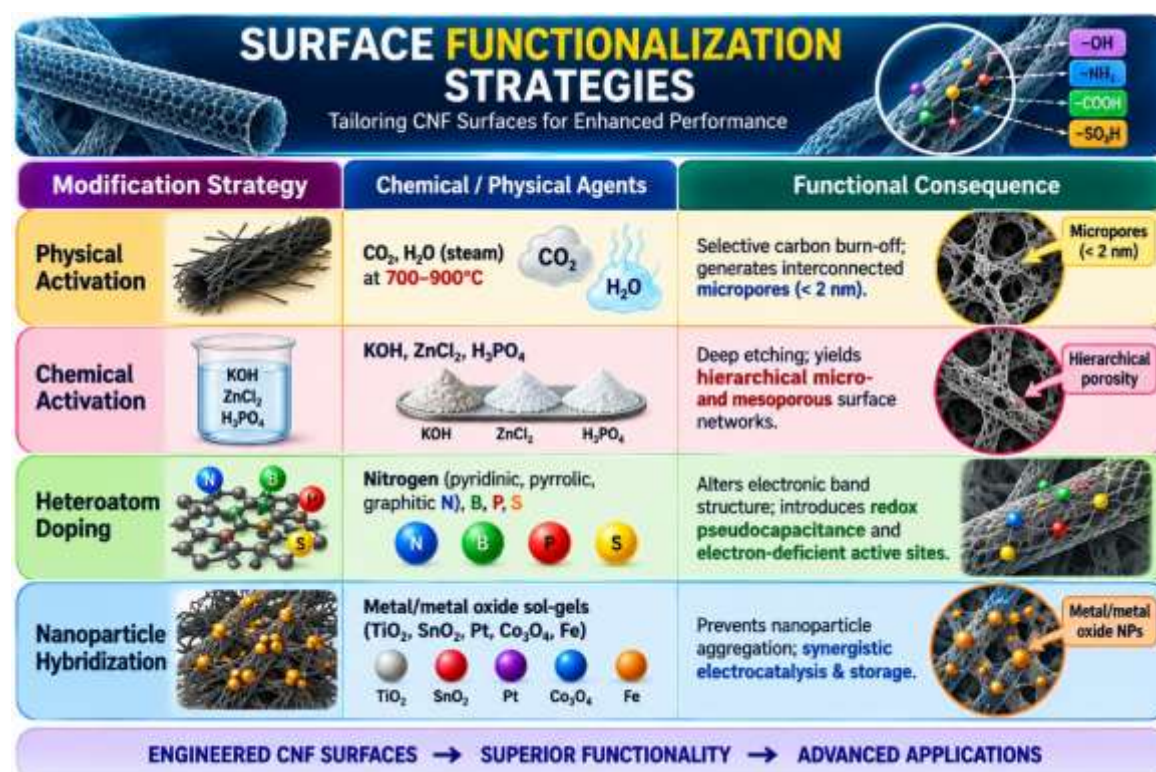
3.1 Chemical and Physical Activation for Porosity Modulation

Developing hierarchically porous CNFs (micro-, meso-, and macropores) promotes mass transfer and electrolyte diffusion:

- **Physical Activation:** Exposing carbonized fibers to oxidizing gases (CO_2 or steam) between 700 and 900 °C selectively removes disordered amorphous carbon atoms through gasification reactions ($\text{C} + \text{CO}_2 \rightarrow 2\text{CO}$; $\text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2$) yielding micropores (<2 nm) without collapsing the fiber architecture [1], [8].
- **Chemical Activation:** Impregnating raw precursor fibers with activating agents such as KOH, ZnCl₂, or H₃PO₄ followed by thermal treatment creates hierarchical structures. Specifically, KOH activation operates via metallic potassium intercalation and oxidation:



Subsequent washing removes dissolved carbonates and metallic potassium, generating CNFs with BET surface areas exceeding 1500–2000 m² g⁻¹ and substantial mesopore volumes [4].



3.2 Heteroatom Doping (N, P, B, S)

Incorporating foreign atoms into the sp^2 carbon lattice modulates the localized electron spin and charge densities, substantially altering chemical reactivity, wettability, and electrical conductivities [1], [5]:

- **Nitrogen Doping:** The most prevalent modification. Nitrogen exists in three major configurations within the carbon lattice: *pyridinic-N* (bonding with two carbon atoms in a hexagonal ring, contributing one p-electron), *pyrrolic-N* (in five-membered rings, donating two p-electrons), and *graphitic/quaternary-N* (substituting a carbon atom in the hexagonal framework) [1]. Pyridinic and pyrrolic moieties impart Lewis basicity and pseudocapacitive redox activity, while quaternary-N preserves high electrical conductivity.
- **Dual and Multi-Atom Doping:** Co-incorporating boron (electron-deficient p-type dopant), phosphorus (large covalent radius that induces local lattice distortion), and sulfur (polarizable electron-rich center) induces synergistic charge asymmetries. This enhances electrocatalytic performance for reactions such as the oxygen reduction reaction (ORR) and oxygen evolution reaction (OER) [1], [8].

3.3 Nanocomposite and Heterostructure Hybridization

CNFs serve as continuous conductive substrates that inhibit the agglomeration and restacking of supported nanoparticles. Co-electrospinning polymer solutions with metal salts (e.g., salts of Co, Ni, Fe, Sn, Ti) followed by reduction or calcination allows *in situ* nucleation of zero-dimensional quantum dots, metallic nanoparticles, or transition-metal oxides directly within the core or anchored onto the sheath of the CNF matrix [1], [8].

4. Applications in Energy Conversion and Storage

The unique 3D nonwoven architecture of CNF mats provides short ion-diffusion pathways, low internal resistance, binder-free operational capability, and continuous electron conduction networks.



4.1 Electrochemical Supercapacitors

Supercapacitors demand electrode materials that combine high electroactive surface areas with rapid ion-transport dynamics. CNF mats serve directly as flexible, binder-free, freestanding electrodes, bypassing non-conductive polymeric binders (e.g., PVDF, PTFE) that impede charge transport [1], [4]:

- **Electric Double-Layer Capacitors (EDLCs):** Activated CNFs store charge electrostatically at the electrode/electrolyte interface. The presence of hierarchical pores ensures that macropores serve as ion reservoirs, mesopores function as low-resistance ionic transport channels, and micropores host the electrochemical double layer [1], [8].
- **Pseudocapacitors and Hybrid Devices:** Decorating CNFs with conductive polymers (polyaniline, polypyrrole) or pseudocapacitive transition metal oxides (MnO_2 , RuO_2 , NiCo_2O_4) couples rapid Faradaic electron transfer with the high rate capability of the CNF backbone. For example, biomass-lignin-derived activated CNF mats have demonstrated specific gravimetric capacitances exceeding $200\text{--}250\text{F g}^{-1}$ in aqueous electrolytes, alongside cycling retention rates above 90% across thousands of charge-discharge cycles [4].

4.2 Secondary Metal-Ion Batteries (Li, Na, K)

In lithium-ion (LIB), sodium-ion (NIB), and potassium-ion (KIB) batteries, graphitic anodes face capacity limits and mechanical degradation under cycling [1]:

- **Mitigating Volume Expansion in High-Capacity Alloying Anodes:** Materials such as silicon (3579mAh g^{-1} for $\text{Li}_{15}\text{Si}_4$) and tin experience severe volumetric expansion ($>300\%$) during lithiation, causing particle pulverization and loss of electrical contact. Encapsulating Si or Sn nanoparticles within hollow or porous electrospun CNFs accommodates this mechanical strain, buffering stress through the structural resilience of the surrounding carbon shell [1], [7].
- **Alkali Ion Intercalation Mechanics:** For larger sodium (Na^+ : $1.02\text{ \AA}$) and potassium (K^+ : $1.38\text{ \AA}$) ions, intercalation into traditional graphite is thermodynamically unfavored or kinetically sluggish. Turbostratic, ungraphitized CNFs feature expanded interlayer spacings ($d_{002} > 0.37\text{ nm}$ compared to 0.335 nm in crystalline graphite) and high defect densities. This expanded lattice architecture facilitates the reversible insertion and extraction of large ions while maintaining cycling stability [1].

4.3 Fuel Cells and Gas Diffusion Layers (GDLs)

In proton-exchange membrane fuel cells (PEMFCs) and direct methanol fuel cells (DMFCs), gas diffusion layers require electrical conductivity, gas permeability, and balanced water-management properties [2]:

- CNF-based freestanding mats carbonized between 1200 and $1400\text{ }^\circ\text{C}$ provide low through-plane electrical resistivity and high mechanical stiffness [2].
- Tailoring the surface hydrophobicity (via post-carbonization fluorination or silanization) creates dual-pathway networks: hydrophobic pores evacuate liquid water to prevent cathode flooding, while hydrophilic pathways facilitate protonic contact [2], [8].

5. Catalysis and Electrocatalytic Transformations

Carbon nanofibers play a dual role in catalysis: they can serve as catalyst supports that stabilize ultra-dispersed nanoparticles, or act as metal-free carbocatalysts through targeted surface functionalization [1], [8].

5.1 Electrocatalytic Water Splitting and Oxygen Reduction

Sustainable hydrogen production and fuel cell operations depend on three core electrochemical reactions:

Oxygen Reduction Reaction (ORR)

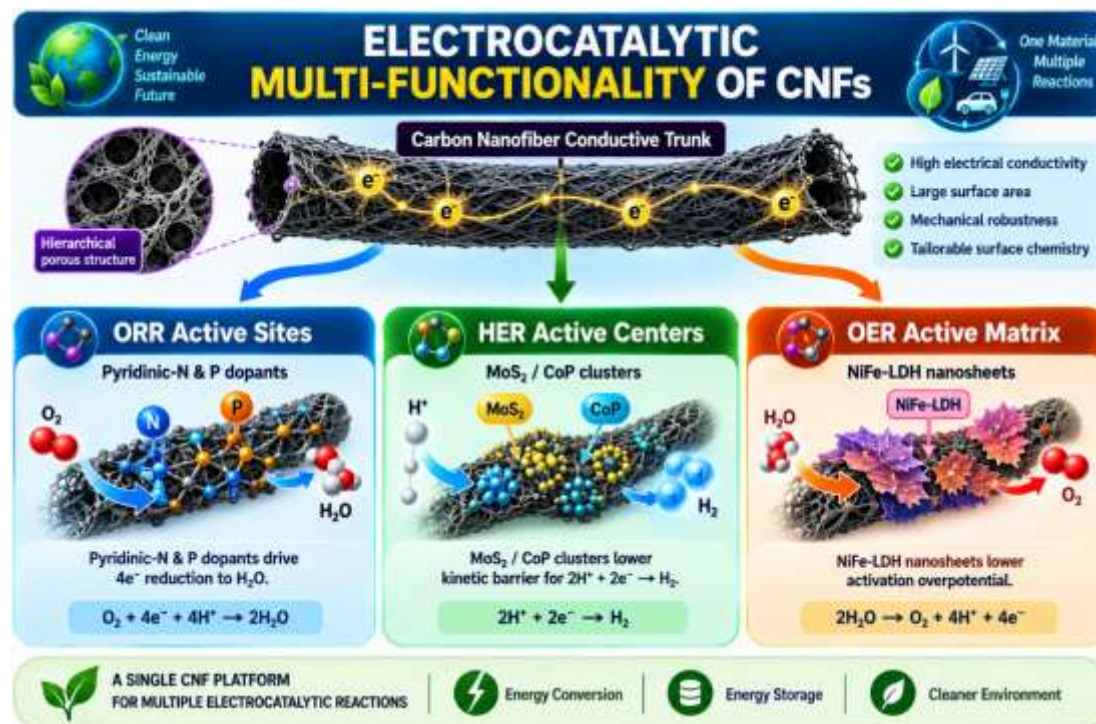
Crucial to fuel cells and metal-air batteries. While platinum-group metal (PGM) catalysts exhibit high activity, their high cost and vulnerability to CO poisoning impede broad deployment. Heteroatom-doped CNFs (specifically N-doped or N, P-codoped variants) redistribute electron spin density, transforming adjacent carbon atoms into electropositive active centers that facilitate the efficient 4-electron reduction of O_2 directly to H_2O ($\text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}$) [1], [8].

Hydrogen Evolution Reaction (HER)

Transition-metal phosphides, sulfides, or carbides (e.g., MoS_2 , CoP , Fe_2C , WC) immobilized on or inside CNFs exhibit high activity across wide pH regimes. The conductive CNF substrate facilitates charge transfer to the active sites while preventing nanoparticle detachment and Ostwald ripening during intense H_2 gas bubbling [8].

Oxygen Evolution Reaction (OER)

The 4-electron transfer kinetics of OER ($4\text{OH}^- \rightarrow \text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^-$) represent the primary kinetic bottleneck in water splitting. Hybridizing CNFs with layered double hydroxides (NiFe-LDH) or mixed-metal spinels (Co_3O_4 , NiCo_2O_4) generates conductive pathways that lower the overpotential required to drive high current densities [1], [8].



5.2 Heterogeneous Catalysis and Advanced Organic Syntheses

The structural integrity of CNFs under acidic, basic, and high-temperature environments makes them effective supports in heterogeneous reactions, such as the selective hydrogenation of alkynes and the oxidation of biomass-derived platform chemicals (e.g., converting 5-hydroxymethylfurfural [HMF] into 2,5-furandicarboxylic acid [FDCA]). The absence of microporous transport resistance ensures that large organic molecules access internal active sites without diffusion limitations [1].

6. Environmental Remediation and Water Treatment

Porous and functionalized CNF matrices serve as effective platforms for addressing environmental contamination in water treatment and air purification [8], [9].



6.1 Adsorptive Decontamination of Heavy Metals and Radionuclides

Industrial effluents contain toxic heavy metal ions and radionuclides that threaten aquatic ecosystems and human health. CNF architectures address these pollutants through distinct surface coordination mechanisms [9]:

- **Electrostatic and Chelation Adsorption:** Introducing oxygenated ($COOH$, $-OH$), phosphorylated ($-PO_3H_2$), or amino ($-NH_2$) ligands onto the surfaces of CNFs establishes coordination sites for polyvalent cations such as Pb^{2+} , Cd^{2+} , Cu^{2+} , and Cr^{3+} .
- **Radionuclide Sequestration:** Surface-functionalized CNF membranes exhibit affinity toward actinide ions such as uranyl (UO_2^{2+}) and thorium (Th^{4+}), demonstrating fast sorption kinetics that conform to pseudo-second-order and Langmuir adsorption models across complex water matrices containing competing background salts [9].
- **Regeneration and Reusability:** The mechanical stability of continuous nonwoven CNF mats allows for simple recovery from fluid streams, bypassing the centrifugation or ultrafiltration steps required when using powdered activated carbons. Acid-washing cycles desorb captured metals, enabling multi-cycle usage with minimal capacity loss [8], [9].

6.2 Membrane Filtration and Particulate Separation

The self-supporting, flexible structure of electrospun CNF mats makes them viable for micro- and ultra-filtration barriers [2], [9]:

- **Size Exclusion and Depth Filtration:** Interlocking nanofibrous networks create tortuous, micron-to-submicron pore channels capable of capturing suspended microplastics, bacterial pathogens, and colloidal particles with low pressure drops [9].
- **Hydrophobic/Oleophilic Separation:** Fluorinated or alkylated CNF membranes can separate oil-in-water emulsions with separation efficiencies exceeding 99%, making them useful for treating industrial oily wastewater and marine spills.

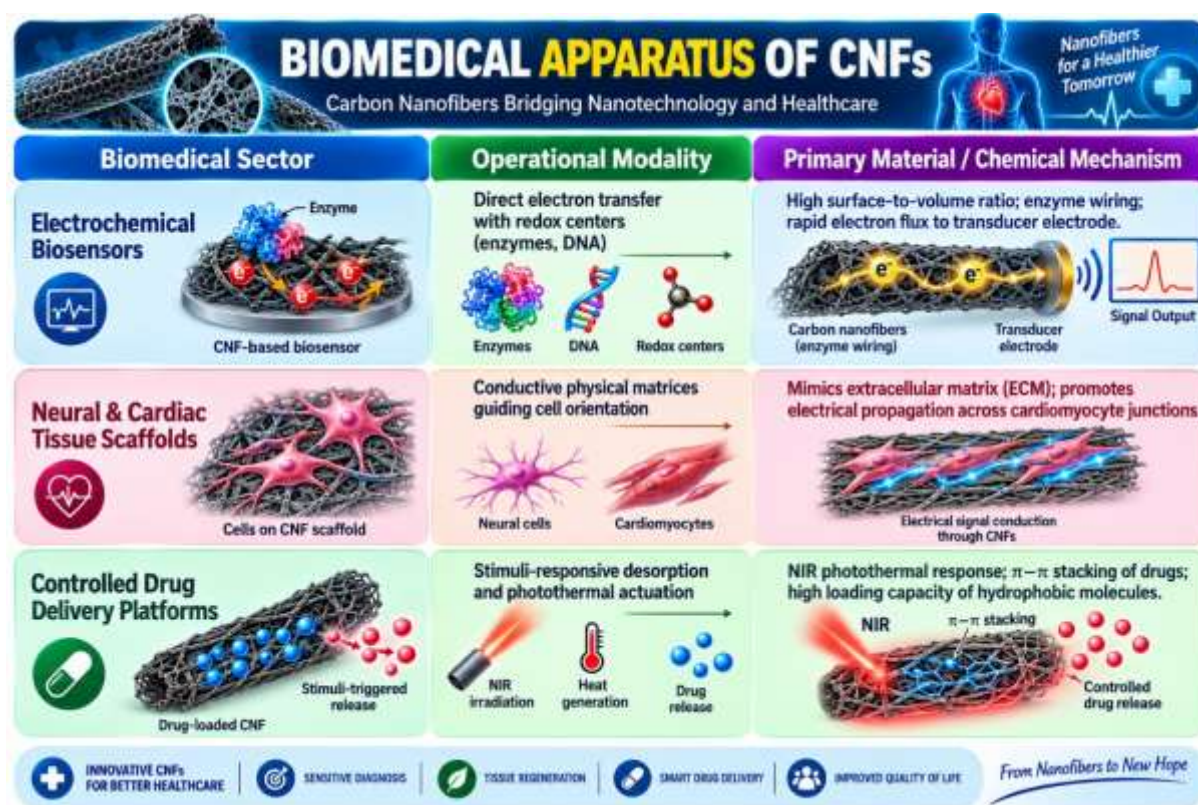
6.3 Advanced Photocatalytic and Persulfate Activation Systems

CNFs serve as functional substrates for photo- and Fenton-like catalysts:

- **Suppression of Charge Recombination:** Incorporating wide-bandgap semiconductors (e.g., TiO_2 , ZnO , $\text{g-C}_3\text{N}_4$, BiOBr) onto the surfaces of CNFs establishes a heterojunction interface. Under light irradiation, photo-generated electrons migrate to the conductive CNF matrix, while holes remain in the semiconductor valence band. This spatial charge separation minimizes electron-hole recombination and boosts the production of reactive oxygen species ($\cdot\text{OH}$, $\cdot\text{O}_2^-$) for decomposing pharmaceuticals, pesticides, and industrial dyes [8].
- **Persulfate Activation:** Metal-free, heteroatom-doped CNFs activate peroxymonosulfate (PMS) and persulfate (PDS) via non-radical and radical pathways, degrading persistent organic pollutants (POPs) without generating secondary transition metal sludge [5].

7. Biomedical and Sensor Applications

Biomedical materials require biocompatibility, appropriate mechanical behavior, and functional responsiveness. CNFs meet these criteria across biosensors, tissue engineering, and drug delivery platforms [1], [5].



7.1 Electrochemical Biosensing Platforms

Electrochemical biosensors convert biological binding events into measurable electronic signals. CNFs provide high surface areas, electrocatalytic properties, and rapid interfacial electron-transfer kinetics [1], [5]:

- **Enzyme-Based Biosensors:** In glucose, cholesterol, and lactate sensing, enzymes (e.g., glucose oxidase, GOx) can be immobilized onto functionalized CNF electrodes through covalent crosslinking (using EDC/NHS chemistry) or physical adsorption. The exposed edge planes of CNFs facilitate direct electron transfer between the deeply buried enzyme cofactor (FAD/FADH_2) and the transducer, producing sensors with broad linear ranges and low limits of detection [1].

- **Affinity and Nucleic Acid Sensors:** Functionalizing CNFs with specific antibodies, aptamers, or single-stranded DNA enables the selective detection of circulating cancer biomarkers, cardiac troponin, and viral nucleic acids, even within complex biological fluids such as whole blood and serum [5].

7.2 Tissue Engineering and Regenerative Scaffolds

Electrospun CNF mats mimic the fibrillar geometry of the native extracellular matrix (ECM) [1]:

- **Electrically Excitable Tissues:** Cardiac and neural tissues rely on electrical signaling to function. Insulating synthetic polymer scaffolds can dampen signal propagation, whereas conductive CNF matrices facilitate electrical continuity across cellular boundaries. Cardiomyocytes seeded on aligned CNF meshes show synchronized beating and enhanced expression of gap-junction proteins (Connexin-43) [1], [5].
- **Bone Regeneration:** Carbon nanofibers coated with nanostructured hydroxyapatite promote the differentiation of osteoblasts and bone tissue deposition, while the underlying carbon matrix provides the tensile strength needed to endure mechanical loading.

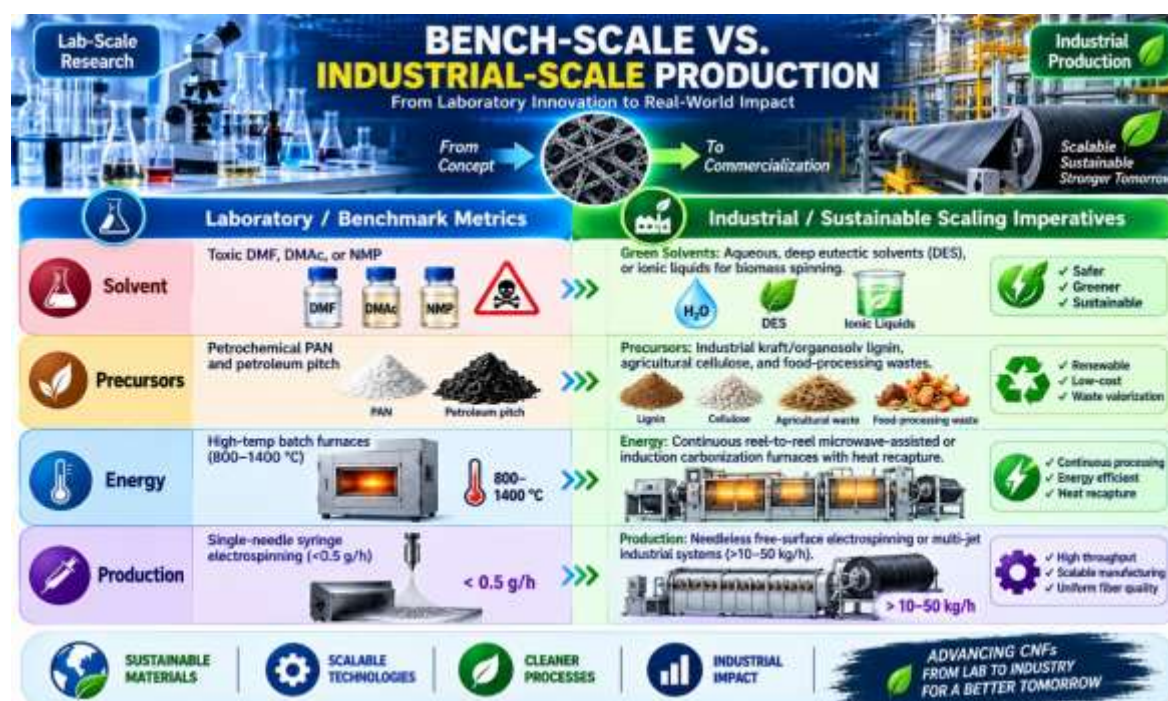
7.3 Stimuli-Responsive Drug Delivery and Photothermal Therapy

The broad optical absorption of CNFs in the near-infrared (NIR-I and NIR-II) spectral windows supports theranostic applications:

- **Chemotherapeutic Delivery:** Aromatic anticancer drugs (such as doxorubicin, DOX) can be loaded onto CNF surfaces at high densities via non-covalent pi-pi stacking and hydrophobic interactions [5].
- **Photothermal Actuation:** Under NIR laser irradiation, CNFs transform incident photons into localized heat via non-radiative plasmonic decay. This local temperature increase destabilizes drug binding, triggering targeted release within acidic tumor microenvironments while inducing hyperthermic ablation of malignant cells [1], [5].

8. Sustainable Perspectives, Life-Cycle Assessment, and Industrial Scalability

To transition CNFs from laboratory development to industrial application, manufacturing routes must satisfy environmental metrics, regulatory safety standards, and economic feasibility.



8.1 Green Precursors and Solvent Substitution

Standard electrospinning relies on toxic, volatile organic solvents such as N, N-dimethylformamide (DMF), dimethylacetamide (DMAc), and N-methyl-2-pyrrolidone (NMP), which present occupational and environmental hazards. Developing green electrospinning systems requires using water-soluble biopolymers, deep eutectic solvents (DES), or non-toxic aqueous solvent mixtures to lower the environmental impact of large-scale production [4], [5].

8.2 Energy-Efficient Carbonization Technologies

Conventional thermal stabilization and carbonization require lengthy residence times and energy-intensive electrical resistance furnaces. Emerging alternatives include:

- **Microwave-Assisted Pyrolysis:** Exploits the dielectric properties of carbon materials to provide direct volumetric heating, reducing reaction times from hours to minutes [4].
- **Continuous Reel-to-Reel Processing:** Integrates waste-heat recovery systems to capture and utilize exothermic energy released during the cyclization of precursor fibers, lowering net operational energy consumption.

8.3 Toxicological Considerations and Life-Cycle Analysis (LCA)

The high aspect ratios and nanoscale dimensions of CNFs necessitate rigorous toxicological assessment:

- Unlike rigid, biopersistent asbestos-like carbon nanotubes, flexible CNFs often exhibit different cellular interaction profiles. However, airborne particulate inhalation during dry cutting, winding, and packaging poses potential pulmonary risks [1], [5].
- Industrial facilities must employ closed-loop containment, wet processing, and robust personal protective equipment to minimize inhalation hazards. Comprehensive life-cycle assessments (cradle-to-gate and cradle-to-grave) are needed to quantify carbon emissions, energy payback times, and the environmental footprint of CNF-enabled devices relative to traditional carbon black or metallic components [4], [5].

9. Conclusions and Future Outlook

Carbon nanofibers (CNFs) are versatile one-dimensional nanomaterials that combine the unique properties of graphene with the practical materials engineering. Their unique combination of high electrical conductivity, tunable porosity, mechanical flexibility and functional surfaces makes them suitable for applications in energy storage and conversion, electrocatalysis, environmental remediation and nanomedicine. The practical potential of these materials is further enhanced by the use of sustainable biomass-derived precursors and by catalytic chemical vapor deposition and scalable electrospinning. The future development should be toward greener and solvent-free synthesis methods with the use of renewable biomass resources, energy-efficient carbonization technologies such as flash Joule heating and continuous microwave pyrolysis, as well as high throughput needleless electrospinning for uniform fiber production. At the same time, standardized procedures for life-cycle assessment and occupational safety are required to assess environmental impacts and to ensure responsible manufacturing. These advances can reduce production costs, improve sustainability and accelerate the transition of CNFs from laboratory-scale materials to safe, scalable and technologically important components for advanced applications.

Conflict of interest

The authors affirm that they have no conflicts of interest related to this work's publication. The research, analysis, findings interpretation, and paper preparation were not impacted by any financial, personal, or professional interactions.

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