

## Research Article

# Environmental Applications of Sorbents, High-Flux Membranes of Carbon-Based Nanomaterials

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Received 1 November 2021; Revised 5 December 2021; Accepted 22 December 2021; Published 2 February 2022

Academic Editor: Lakshmipathy R

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Carbon-based nanomaterials have unique and controllable properties, making it possible to find and treat environmental challenges. There are several environmental applications for carbon-based nanoparticles: sorbents, membranes, antimicrobial agents, and sensors. According to this review, carbon-based nanomaterials have a variety of environmental benefits. This article also looks at prospective uses of nanomaterials in environmental systems, utilizing carbonaceous nanoparticles as a guide for their physical, chemical, and electrical properties.

## 1. Introduction

A growing body of environmental research is focused on nanomaterials, which are being investigated as potential contaminants. Explaining how engineered nanomaterials affect the environment can help in the risk assessments and help in the development of safe new materials. However, focusing solely on the implications may obscure the wide range of nanotechnology applications being pursued in order to enhance environmental results in the long run. Carbon-based nanomaterials' tunable physical, chemical, and electrical capabilities spur new approaches to tackling long-standing environmental problems.

Biomedical nanotechnology advancements have made it possible for environmental science and engineering to make similar gains. For example, synthetic transmembrane pores made of functionalized nanotubes and carbonaceous nanomaterials are employed to optimise drug fate and transport in thick tissues [1, 2]. Examples of analogous environmental

applications include the targeted delivery of restorative agents, the specifically planned removal of dangerous substances, and new membrane structures for water filtering. As stated in this review, carbonaceous nanomaterials have both proactive (avoid environmental degradation, increase public health, and optimise energy efficiency) and retroactive (improve energy efficiency) environmental purposes. Wastewater reuse and pollutant transformation are all examples of remediation. Begin by learning more about carbonaceous nanomaterials and some of their unique properties. Further research will examine some of the most cutting-edge applications for carbon nanotechnologies in domains including sorbents and membrane separations with high flux rates.

Recent developments in the rational design and manipulation of nanomaterials have made a wide range of new technologies possible. Since carbonaceous nanoparticles have unique properties that allow for environmentally friendly uses, they can be created and deployed responsibly.

## 2. Carbon Nanomaterials in Nanotechnology

Molecular manipulation makes use of unique nanoscale properties by combining a variety of substances. These nanotubes and fullerenes with carbon, boron, MoS<sub>2</sub>, WS<sub>2</sub>, NbS<sub>2</sub>, TiS<sub>2</sub>, chrysotile (asbestos), and other precursors have exceptional physical-mechanical-electrical properties when compared to their bulk counterparts [3]. Unlike inorganic nanostructures, carbon nanostructures allow for custom modification due to their unique hybridization and sensitivity to changes in the synthesis conditions. Even while inorganic nanomaterials hold enormous potential for the future, carbonaceous nanostructures have research and applications that are far further along right now. The potential for carbonaceous nanoparticles to be utilised in environmental systems is also being investigated seriously.

There is a strong correlation between the physicochemical and electrical properties of carbonaceous nanoparticles and how much carbon has hybridised in their structural shape [4]. Three electrons are located in the ground-state orbital arrangement of carbon, with two in each of the other's orbitals. When an electron is in a lower energy s orbital, it is much easier for it to jump to the higher energy p orbital, which is free in the ground state. In accordance with the bonding interactions with the neighbouring atoms, this promotion allows carbon to hybridise into a single- or double-sp<sup>3</sup> structure. The higher energy state of the electronic arrangement can be compensated for by covalent bonding with nearby atoms, which provides ample energy. Out-of-plane bonding between unhybridized P orbitals causes compensation in both the sp<sup>2</sup> and sp<sup>3</sup> hybridization phases, but this compensation is nearly equivalent for both [5].

Different hybridization states lead to various organic compounds and various bulk carbon structures (Figure 1). As a result of being subjected to extreme heat or pressure, carbon develops a diamond-like trigonometric sp<sup>3</sup> structure. If made at lower temperatures, carbon has the planar sp<sup>2</sup> conformation, which results in a monolayer sheet bound by three sigma covalent bonds and a single bond. van der Waals forces and the interaction between overlapping parallel sheet orbitals combine to produce weak out-of-plane interactions.

Shear pressures, separation, or chemical change can disrupt graphite's planes, causing it to slide past one another when under weak interplanar stresses.

When compared to two-dimensional graphite sheets, nanoscale graphite sheets have greater thermodynamic solidity than the former. The number of negative dangling bonds is reduced, reducing the stress electricity generated by the planar graphite's curvature [6]. In addition to having the same functions as graphite, fullerenes, and nanotubes have unique and controllable properties due to quantum results at the nanoscale, better sp<sup>3</sup> man or woman of the bonds, and quantum confinement of wave characteristics in one or more dimensions [7]. Carbonaceous nanostructures have the same bonding arrangements as macroscopic carbon structures, but their residences and morphology are determined by the stability of particular resonance systems rather than the majority averages of their crystal bureaucracy.

*2.1. Fullerenes.* Due to their electrical form, fullerenes have chemical, optical, and structural properties that can be manipulated. A disease-free fullerene has a total of twelve 5-member earrings and an unknown number of 6-member rings. Structures lacking hexagons are more likely to have strong sp<sup>3</sup> bonding, resulting in increased stress. Carbon sites that are more reactive have also been found in those specimens. Because resonance systems delocalize bonds over the fullerene form, isomers with neighbouring pentagons have lower stability and relative abundance than isomers with remoted pentagons because of this [8, 9]. C-60 is an aromatic molecule, although chemically it acts like a nonaromatic molecule [10].

Degenerating C-20 fullerenes and inactive, planar graphite are distinguished from buckminsterfullerene (C-60), which exhibits a delicate equilibrium between balance and reactivity. C-60 has a resonance shape that supports a similar digital nation and geometry in terms of each carbon atom's digital nation and bonding geometry (thirteen). C-60 has a clean existence because of its inherent symmetry as a chemical process initiating fabric. Polymeric substances for a wide range of environmental utility areas require the employment of covalent, supramolecular, and endohedral variations to govern molecules and form polymeric substances.

The bottom unoccupied molecular orbital of C-60 can contain up to six electrons despite its high oxidation resistance (LUMO). Fullerenes can now serve as structural scaffolds for chemically reactive adducts in covalent chemistry, and this opens the door to new applications. Diederich and Thilgen [11] show that throughout the preceding decades chemistry of covalent fullerenes has evolved substantially.

Supramolecular approaches for fullerene modification has to be developed in order to take advantage of environmental considerations. The noncovalent van der Waals, electrostatic, and hydrophobic interactions inherent to fullerenes and their component reactants can be exploited using supramolecular techniques to initiate molecular self-assembly. Hydrophobic fullerene molecules can be made more soluble via supramolecular techniques that boost solubility while restricting aggregation in biomedical and environmental applications [12]. Through the use of such methods, secondary architectures ranging from simple monolayered films to complex three-dimensional macrostructures can now be precisely controlled [13]. An increase has been seen in the number and variety of custom structures that can be created using covalent and supramolecular approaches [14].

It is hard to believe how many different properties may be found in carbon nanostructures like fullerenes because of their electric and conductive properties. A wide range of research interests have sprung up around the endohedral doping modification in these electric dwellings. A solitary swap photosensitivity and binding power effects can be achieved by substituting a single atom in the fullerene form [15]. Fullerene cages can be used for a variety of electrical modifications, interstitial atom transport, dissolution, and vapourization of typically refractory metals when endohedrally doped, all with relative ease. It has a diaphragm already

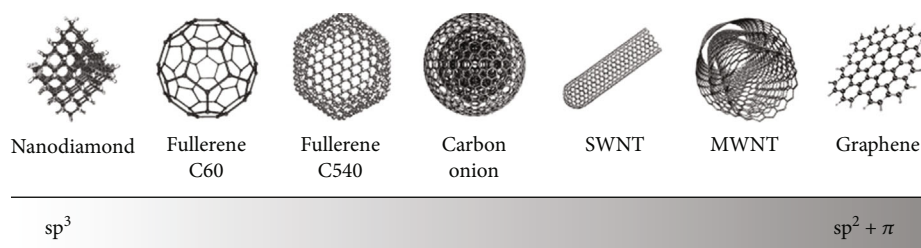


FIGURE 1: Carbon-based nanomaterials in various levels of hybridization. The predominant hybridization state of carbon-carbon bonds controls several chemical and electrical characteristics of carbonaceous nanomaterials.

in place in the cage [16]. Although ionic interactions and price transfer can cause fullerene rehybridization, this is not always the case. A variety of fullerene morphologies have been tried in carbonaceous nanomaterials, including huge spherical fullerenes [17, 18] and a family of concentric fullerenes known as carbon onions [19]. Molecules with this level of symmetry and bonding have a very high degree of reactivity. If carbon anions and huge fullerenes behave as anticipated theoretically, they will have a faceted shape. Direct imaging instead of C-60's conical form shows that these molecules are circular. Therefore, Stone-Wales flaws were proposed as crucial conventional bonding form characteristics [20]. Four six-member rings are rearranged into a five-7-7-5 pattern via Stone-Wales faults. The numbers are five, seven, seven, five [21]. A nucleophilic assault is more likely when the form has a lower resonance and a bigger pressure energy.

Water at environmentally relevant pH and electrolyte concentration [22–25] has a unique inclination to produce stable crystalline nanoparticles (25–500 nm in diameter) due to the fullerenes' ability to do so. This notion does not hold up when humic acid is absent, as there is no data to support it [23]. Because pH, ionic strength, and mixing behaviour all have an effect on aggregate diameter [26–28], the average aggregate diameter is a function of each of these three variables. Micro- and nanoparticulate adsorptions of macromolecular compounds on fullerene nanoparticulate surfaces help to stabilise and reduce aggregation rates when humic acid is present [29].

*Nanotubes:* CNTs are a necessary initial step to fully comprehend zero-dimensional fullerene in a single dimension [30].

**2.2. Molecules.** Graphene sheets folded into nanoscale cylinders and topped with spherical fullerenes are the building blocks of nanotubes. Making CNT structures with a high aspect ratio by trimming down their sizes from nanoscale to micro- and centimetre scales is possible. More than one comprehensive review of carbon nanotubes has been published [5, 31]. This brief overview of carbon nanotubes (CNTs) focuses on their place in the hybridization spectrum, and the impact this conformation has on environmental-relevant properties.

Like graphene's hexagonal  $sp^2$  structure, CNT sidewalls have a spherical fullerene-like appearance. Nanotubes, unlike their zero-dimensional cousins, have a finite amount of curvature. In comparison to spherical fullerene molecules,

CNTs have a lower resistance to chemical alteration and rearrangement due to their higher  $sp^3$  character in this bonding configuration.

Nanotubes, on the other hand, differ significantly from graphene planes. Radial and circumferential information is quantumly confined by tubule's one-dimensional shape [7]. Because of its unique dimensional hexagonal structure, two-dimensional graphene is structurally ambiguous when reduced to a single size. The rolled graphene sheet's rotational direction has a significant impact on the CNT's electronic houses. Due to the hexagonal lattice orientation, even though bulk graphite is a semiconductor, SWNTs with tiny diameter exhibit metallic, semimetallic, or semiconducting properties [29]. It is difficult to filter out monochiral nanotubes due to high-yield manufacturing strategies, which limits the commercial and environmental applications of SWNTs.

Multiwalled and double-walled nanotubes are the one-dimensional equivalents of carbon onions (MWNTs). They share numerous features with SWNTs due to their small interlayer coupling [3] across a 0.34 nm distance. Swept-wire nanotubes have metallic properties like bulk graphite, but MWNTs have semiconducting properties instead. The strong attraction interactions that exist between the nanotubes make purification and manipulation of CNTs more difficult. It is due to their work that carbon nanotubes have such a compact structure [1] and low dispersion.

This dispersion can be achieved in both polar and apolar liquids alike. For the separation of nanotube sheaths, sonication is an effective physical dispersion approach. Other options include the utilisation of natural polyelectrolytes, aromatic polymers, or DNA exfoliation [32]. The exfoliating agent's aromatic components interact with the nanotube sidewall's orbitals via these supramolecular debundling channels, preventing bundle formation sterically [19]. The use of supramolecular techniques to disperse CNT bundles is efficient, but their utility is limited in systems that make use of pure nanotube properties.

Fullerenes with higher solubility are more difficult to work with because of the dispersion problem. Controlling molecular manipulation is more difficult for nanotubes despite progress in functionalization and supramolecular modifications [4, 8]. Because sidewall hexagons limit carbon's reactivity, they necessitate the employment of stronger reagents to compensate for the reduced strain energy. SWNT functionalization chemistry has been compared to fullerene chemistry in a number of studies [4].

Commercial SWNTs and MWNTs have several defects, metal contamination, and physical heterogeneities. Because there are so many various ways to purify CNTs, it is challenging to do research on the ramifications and practical applications of these materials [4]. As a result of the synthesis's inconsistencies, rather than single nanotube characteristics such as strong conductivity or effective area emission, most proposed environmental programmes for CNTs use bulk homes like large surface locations.

### 3. Carbon-Based Nanomaterials Possess Unique Characteristics

For the first time, researchers have created a new class of carbon materials that incorporate hybridised two-dimensional sp<sup>2</sup> bonds with extraordinary nanoscale properties from physics and chemistry. Environmental systems could be made more effective by using nanomaterials' electrical conductivity, adsorptive capacity, and other single-molecule and bulk properties (Table 1). While carbonaceous nanoparticles can be used in environmental applications because of their size and shape, they also have molecular interactions and sorption properties that make them helpful in other fields as well.

Length, width, and height are all measurements. In molecular manipulation, shape and conformation of a material can be controlled. The fullerene cage structure of carbon nanostructures affects properties of homes like as size and chirality. Despite the absence of general precision and homogeneity in present nanoscale carbon structure manufacturing procedures, linkages between increasing circumstances and output are a valuable resource for the synthesis of customised nanomaterials. The form and purity of nanomaterials are optimised in conjunction with physical orientation for specific applications using a variety of fuels and catalysts. HiPCO synthesis can produce nanotubes as small as 0.7 nm because of the strong correlation between SWNT diameter and the synthesis technique. Graphitic-based overall methods, such as laser ablation, are used to make nanotubes as small as 2–2 nm (forty-seven).

The diameter of fullerene and tubular nanostructures has a significant impact on their properties and uses. A fullerene's diameter is determined by the number of carbon atoms in the sphere. C-60's inner diameter must be less than 0.7 nm to meet the stabilising pentagon isolation criteria. The diameters of swept-wire nanotubes are also in this range; however, typical sizes of roughly 1.4 nanometers have been recorded for a number of commercial synthesisers [8]. A reduction in SWNT diameter increases mixing of and bonds as well as rehybridization of electron orbitals. As a result of the bond structural changes in SWNTs, their electrical, optical, mechanical, elastic, and thermal properties all change for the better. Environmental systems benefit from understanding physical size exclusion and capillary behaviour in addition to nanotube diameter dependency. In innovative moulding, separation, and size exclusion methods, such as the production of nanowires [5], nanotubes have been used with their small inner diameters, for example in membrane filtering [1]. Purification techniques

required by bulk nanotubes' small inner diameters have hindered CNT application, but that has not prevented scientists from exploring novel things with them [3, 5]. The combination of a tiny diameter and a long tubule length in nanotubular formations gives them an extraordinarily high aspect ratio. Additional information on high aspect ratio nanomaterials' features and applications can be found in the reviews referenced above [2, 4–6].

Micro- and macroscale carbonaceous nanomaterials take pride in their superior surface-to-to-quantity ratios. Among most fabric and nanoscale structure, loose strength differential is expressed by  $G$ , which increases  $G_{\text{surface}}/G_{\text{volume}}$  ratio at nanoscale [5]. For this reason, species found on the nanotube floor have higher surface atom concentrations due to their greater adsorptive capacity and broader utilisation as scaffolding materials. On the other hand, aggregation (bundling) and chemistry are important drivers of size, shape, surface location, and other trends for carbonaceous nanomaterials. Individual nanomaterial dwellings are the focus of most research. When vaporizable, biomolecular, and metal contaminants adsorb on nanomaterial floors, their aggregation behaviour, thermal and electric-powered features, mechanical energy, and physicochemical homes can be affected. Large physicochemical features have been linked to secondary nanomaterial aggregation formations. First, these issues must be rectified before carbonaceous nanomaterials can be used in a wide range of applications.

*3.1. Properties of Sorption and Molecular Interactions.* In order to better understand the molecular interactions, sorption, and partitioning features of fullerenes and nanotubes, researchers are using a combination of theory and experimentation. Carbonaceous nanoparticles are supported by numerous well-established physical-chemical models and theories, such as electrostatics, adsorption, hydrophobicity, and Hansen solubility factors [6, 11]. It has been possible to display physical and chemical tactics at the nanoscale by molecular modelling of heterogenous nanotube samples that may not be otherwise reached through experimental approaches, regardless of the excessive processing requirements.

Carbonaceous nanoparticles' interaction potential electricity is characterised using the traditional Lennard-Jones (LJ) continuum model [21, 22]. The LJ version includes information on van der Waals attractive forces (Kessom, Debye, and London forces) as well as Pauli repulsion caused by electron orbitals overlapping at very short separation distances [21]. Geometries display a strong connection to the perception of a universal graphitic ability while accounting for geometry-precise empirical constants [31].

DLVO colloidal stability is supported if fullerene nanoparticle surface fee in aqueous solutions is due to electrostatic interactions between fullerene nanoparticles [23]. As a result of steric challenge and polar functional companies, hydrophobic nanoparticles are functionalized using covalent or supramolecular techniques to reduce aggregates [7, 11, 14, 29]. In a 1:1 aqueous electrolyte, researchers observed that the powerful Hamaker constant for fullerene nanoparticles becomes 6.9 (10<sup>-21</sup> J), which corresponds to



TABLE 1: Unique features of carbonaceous nanoparticles are applied in environmental systems. Carbonaceous nanomaterials, in both their individual and bulk forms, exhibit distinctive characteristics. The spectrum of environmental applications for carbon-based nanomaterials will be expanded through further characterization of their properties, production methodologies, and purification procedures.

	Environmental Applications						
	Pollution Prevention	Sorbents	Composite Filters	Energy Storage	Antimicrobial Agent	Aligned CNT Membranes	Sensors
Physical Properties	Size	X	X		X	X	X
	Shape				X	X	
	Surface Area		X	X	X		
	Molecular Specificity		X		X		X
	Hydrophobicity		X	X		X	X
	Electrical Conductivity				X		X
	Optical Activity		X				
	Thermal Conductivity	X			X		
	Bulk Properties	X					
	Individual Properties	X					

other organic and biological particles present in aquatic environments [23].

Hydrophobicity grows as particle water interaction improves. One of the solute molecules is hydrophobic, which increases the likelihood of an unfavourable interplay between them compared to one that is hydrophilic [8]. This combination has significant effects on water evaporation and drying because of its hydrophobic properties (C-60 and CNT hydrophilicity) (seventy-three). For CNT molecules in water, there appears to be energy required to rupture water-to-water couplings, while also generating a hollow area for the CNT that acts as the greatest barrier to dissolution (eighty).

There was some early speculation that the capillary forces in nanotubes could be unusually powerful, pulling molecules from the fuel or liquid section via van der Waals attractive forces and dipole interactions with polar molecules to generate molecular “straws” [10]. As moisture was eliminated from the equation for nanotube capillarity, numerous gaps appeared in the research. They amended their version with estimations for nanotube capillarity for metal expansion, based on the Laplace equation by Dujardin et al. [32].

There are more electrostatic contacts since the medium has less polarizability; therefore, water confinement entropy costs and enthalpic losses due to fewer hydrogen bonding partners are compensated for (seventy-five). Due to low cohesive forces or powerful intermolecular interactions, most natural solvents and water can wet nanotube surfaces via capillary action; however, liquids with a high floor anxiety level cannot [33]. Wettability is projected to be limited by surface tension limits of 72 mN/m (eighty-two, eighty-three). It is inversely proportional because of the difference in capillary action pressure in nanotubes. Because of this, the nanotube interior diameter has the power to drastically alter fluid float and capillarity properties (diameter of a nanotube used inside).

In addition to hydrophobicity and capillarity, the adsorption behaviour of sorbates and orientation on small carbons are controlled by their molecular characteristics. In order to control the sorption mechanism of unfunctionalized nanomaterials, physisorption is used (84). Adsorption experiments reveal fast equilibrium costs, exceptional adsorption capacity, little pH sensitivity, negligible hysteresis in dispersed nanoparticle samples, and consistency with standard Langmuir, BET, or Freundlich isotherms [11, 13, 32].

The unusual adsorption features of micropores, on the other hand, continue to confound scientists who study them. As the distance between carbon layers rises, the amount of electricity dispersed increases as well, resulting in stronger sorption interactions between them. It all comes to a head as condensation forms inside the nanotube [15]. There may be a rationale for nanotube “filling” if some models predict an adsorption potential greater than the actual surface area of a CNT. Adsorption potential has an effect on both pollutant removal and hydrogen storage in environmental applications.

The properties of electronic, optical, and thermal devices are all included in this term. As a result of its unique conductive, optical, and thermal properties, fullerene/nanotube bonding offers tremendous application potential. While unique field emission properties, optical nonlinearity, high thermal conductivity, and low temperature quantum phenomena may appear unrelated to traditional environmental applications, redesigning energy and material-intensive consumer electronics has significant indirect environmental benefits [8]. Examples include the development of new photovoltaic cell architectures made possible by carbon-based nanomaterials with better electrical characteristics [9]. Environmental cleaning employing persistent organics and fullerene-mediated photooxidation has also been studied.

A unique property of fullerenes is their great optical activity in the UV and visible spectrums. Visible spectrum

high absorption bands are linked to electron transitions from bonded to antibonded orbitals in the UV and between visible HOMO and LUMO bands, respectively. Strong UV absorption leads the fullerene molecule to be photoexcited from the ground state to the singlet-excited state. This excited-state decays in aqueous solutions containing common ambient solutes in 1.2 ns [13], but the emission wavelength can still generate a variety of reactive oxygen species (ROS), such as singlet oxygen molecules, superoxide radical anions, and hydroxide radicals in aqueous solutions [14]. Researchers employed a mechanistic framework for photosensitization to better understand how fullerol and nC-60 function [34]. Close packing of fullerene molecules in crystalline nC-60 nanoparticles, on the other hand, results in triplet-triplet annihilation and self-quenching, substantially reducing the photochemical reactivity of the system [14, 15]. Fullerene biocompatibility in watery environments and the significance of understanding how nanomaterials collect in nature as a result of ROS generation have been sparked as a result [14].

Several electronic features of SWNTs have received considerable interest, including their ability to adjust the spacing between neighbouring carriers, their low ionisation potential, and their ability to generate light on the field. A variety of nanotube properties can be explained using the electron flow confinement idea [4]. Chirality, diameter, length, and the number of concentric tubes all affect the electrical characteristics of nanotubes [9] (most of the MWNT heterogeneities).

Electron mobility [9–12, 32, 33] and defect dispersion limit the use of these materials in consumer and environmental goods. It has been established that the chirality and diameter of nanotubes affect the size of band gaps based on current research. The SWNT chirality is indexed using an indexing coordinate system that assigns an indexing coordinate system indexing numbers  $(n, m)$  to specific atoms on the graphene sheet's flat surface [26]. Depending on the armchair conformation, there can be up to two metal tubes with the same diameter and curvature with zero-bandgaps in between them. Carbon-atom-arrangement  $(n, m)$ -nanotubes are semiconductors with small or big gaps. With increasing semiconductor nanotube diameter, the gaps become reduced until metallic characteristics resembling those of an armchair are observed, as indicated in the figure [15]. This behaviour is similar to graphite's in electrical terms since the electronic structure of the outermost tubules dominates the conduction in MWNTs [4].

In metallic SWNTs, electron confinement causes the conduction bands to be quantized into discrete energy levels in the radial direction" [11, 13]. A nanotube has unique electron states, and electrons dispersed over a larger area of the nanotube via resonant tunnelling transit through them using this approach. Conduction and current capacity are both improved by spatially spreading the charge, and sidewall flaws are reduced as a result. Additionally, some dopants serve as intercalates for charge transport across the sp<sup>2</sup> hybridised sidewalls' planar structure [14, 15], or as metallic features by modifying the local electronic density of states (EDS) [34]. Given that SWNTs' conductivity is highly

dependent on the adsorption of liquid or gaseous molecules nearby, they have found extensive utility as environmental sensors.

Because of their reduced ionisation potential, SWNTs are less ionising in the electronics industry. SWNTs, if you want to move an electron from its ground state to its excited state, you will require a lot of ionisation potential energy. To put it another way, the voltage required to excite an electron and compel its emission is decreased in field emitters with low ionisation potential. Due to charge delocalization and narrow diameters, SWNTs are superior at guiding electron emission since they do not accumulate as many electron holes on the tube [10]. Adding adsorbates like water reduces the ionisation potential even more [11]. Using nanotubes to reduce voltage potential and boost field emission efficiency, next-generation green gadgets will be more energy-efficient.

Thermal conductivity is another impressive property of CNT tubules and assemblies. When seen in bulk, tube-tube junctions are the primary source of thermal conductivity barriers. New methods for linking nanotubes [12] could simplify the process of fabricating long fibres with high thermal conductivities.

*3.1.1. Sorbents Made of Carbonaceous Nanomaterials.* In both natural and manmade environmental systems, sorption of contaminants to sorbents such as NOM, clay, and activated carbon serves as a major pollution sink (AC). Sorption processes such as those used in traditional drinking water treatment remove organic and inorganic pollutants from water by using physicochemical means. Decades of research have given us a greater understanding of sorption mechanisms, allowing us to further optimise sorbent qualities. Sorptive capacity is limited in typical carbonaceous sorbents due to several reasons. These include surface active sites' density, the activation energy of sorbent bonds' covalent bonds, sorption in heterogeneous systems' slow kinetics, and the pace at which mass moves to the sorbent's surface. Because conventional sorbents are so large, they have difficulty moving in low porosity situations. Since they have a huge surface area to volume ratio, regulated pore size distribution, and tamperproof surface chemistry, carbonaceous nanosorbents outperform traditional ones. According to the results of sorption studies conducted with carbon-based nanoparticles, these nanoparticles have high adsorption capacity, high equilibrium rates, and efficiency throughout a wide pH range [19–24].

Hydrophobic, dispersion, and weak dipolar forces influence water-based sorption systems and are also responsible for organic pollutant direct sorption on nanomaterial surfaces (pages 18 and 19 in the source). There is less equilibrium rate for activated carbon in comparison to carbonaceous nanosorbents, and there is also less adsorption energy heterogeneity in the sorbents due to the interactions with aromatics in the sorbents [5, 10, 28, 32, 33]. For this reason, Chen and Elimelech et al. [29] investigated a variety of carbonaceous nanosorbents such as C<sub>60</sub>, nC<sub>60</sub> nanoparticles (SWN), and MWNTs to get to this conclusion (microwave nanotubes). As a further benefit of using carbonaceous nanopowder, there is no hysteresis between the adsorpt-

and desorbpt-isomers for liquids and gases [4, 7, 33]. nC-60 aggregates in the intraparticle area are critical for gas adsorption in hydrogen storage, and decreasing the energy barrier to filling them can restore system hysteresis.

These systems have increased interaction potential because their geometry is more complicated and hence has more nonspecific van der Waals interactions that boost SWNT adsorption. For gaseous adsorption on SWNTs, researchers conducted Monte Carlo simulations to figure out the appropriate pore diameter. Tetrafluoromethane adsorption requires nanotube diameters of 1.05 nm or smaller because of the optimal balance between high binding energies (enthalpies of adsorption) and storage space [15]. Carbon nanostructures that are most successful at eliminating specific contaminants can be predicted using similar models.

Activated carbon has long been used in water and wastewater treatment to remove organic contaminants and any remaining tastes or odours. As a result of its high cost and possible toxicity, carbonaceous nanosorbents have not been extensively studied in water treatment applications. Despite the absence of published evidence on nanosorbents' performance in immobilising various nanomaterials, Kroto et al. [34] advocated adding them into typical packed-bed reactors. Toxic pollutants like trihalomethanes [11], polycyclic aromatic hydrocarbons [11], and naphthalene [11] have been researched extensively using nanosorbents [15].

Even though carbonaceous nanosorbents have impressive sorbent capacities and fast equilibrium rates, their advancements are merely incremental. Using nanosorbents, it is possible to accurately modify the surface chemistry of fullerene and nanotubes. Utilizing carbonaceous nanoparticle bottom-up synthesis and selective functionalization, specific adsorption qualities can be designed into the current collection of conventional sorbents. Functionalized nanosorbent may provide a more effective way for targeting specific micropollutants, removing low-concentration contaminants, or improving subsurface mobility [9, 11]. Hydrophilic CNTs outperformed activated carbon when modified with hydrophilic sOH and sCOOH groups while sorbing low molecular weight and polarity chemicals [32].

Organic sorption was found to be less selective than inorganic sorption on carbonaceous nanostructures, according to hydrophobic sorption mechanisms. Total surface area no longer determines inorganic sorption capacity; instead, the density of surface functional groups does. Both metal speciation and competing complexation events, as well as variations in pH, can affect sorption capacity. Another hypothesis is that arsenic, an oxyanion metal pollutant, has deprotonated oxygen groups bridged to it on the sorbent surface by a ternary surface complex process, which changes with the concentration of divalent cations in solution [12].

Furthermore, carbonaceous nanoparticles have been used as high surface area scaffold for sorbent oxides or macromolecules with intrinsic capacity in addition to direct sorbent functions. Since covalent chemistry has advanced, nanoscaffold materials can now be created with colours, metals, and radionuclides in solution in mind. Scaffolding agents for contaminants removal have recently used nano-

materials such as amorphous alumina [12, 13], polypyrrole for perchlorate separation [14], and polypyrrole for perchlorate separation [6]. A great deal of recent study has centred on metal preconcentration, extraction, and oxidation. Even if the synthesis costs are higher, activated carbon is more expensive than single- and multiwalled nanosorbents, according to recent studies (148). Using sorbent nanoparticles for more than merely eliminating or remeasuring common pollutants is an option. Further portions of this review include topics like fullerene and MWNT-assisted metal preconcentration [11, 12], hydrogen adsorption on SWNTs in fuel cells [12], virus adsorption on SWNT-based drinking water filters, and CNTs as single-molecule environmental sensors [32].

### 3.1.2. Aligned CNTs as Selective High-Flux Membranes.

Traditionally, RO desalination membranes used a dense polymeric film barrier to separate components based on the rate at which a solution diffuses across the membrane. As a result of these separation mechanisms, modern membrane design must choose between selectivity and water flux as a primary design goal. There will be tremendous progress made in diffusion-based membrane performance even if polymeric RO membranes remain the leading desalination technique. This could lead to significant energy and financial savings [33].

Aligned nanotubes act as filtering pores inside an impermeable support matrix. Diederich and Thilgen were the first to create this sort of membrane (Figure 2) [11]. Gold nanotubes with a customised form and constant inner diameter were used in separation investigations with a mixture of two organic solvents for low molecular weight solutes while maintaining high permeate flow. It has been possible to enhance steric selection with chemical and/or charge-based selectivity by using CNTs because of their varied properties and numerous functionalization techniques. The alteration of parameters like surface hydrophobicity and nanotube tip function of the channel gated diameter [1] [13, 14]. Asymmetric membranes in desalination and other membrane-based osmotically driven technologies, like forward osmosis and pressure retarded osmosis, have an internal concentration polarisation problem that must be solved by using aligned nanotube-based membranes instead of typical asymmetric ones. By their very nature, these membranes are symmetric. High-flux aligned CNT membranes used in recent experimental work with enhanced water treatment applications have proven promising thus far. Already mentioned are the MWNTs employed by Hinds et al. to build nanoporous membranes [13]. However, owing to its large inner diameter (>4 nm) and wide distribution of pore sizes, this early membrane is better suited for ultrafiltration than desalination. It was Martin and Kohli's [1] surprise that they were able to enhance size selectivity while maintaining the same mass. Using CNT membranes that have inner diameters under 2 nm, researchers could measure transport rates in nanometer-scale regions.

Carbon nanotube membranes have progressed from size exclusion sieving devices to nanofiltration membranes with variable permeability and configurable size exclusion. An

Gold nanotubule (Jirage et al., 1997)
<i>Macromolecular separation.</i>
Bottle-neck tubule (Jirage et al., 1997)
<i>Narrow entrance, wide pore for increased flux.</i>
Aligned MWNT membrane (Hinds et al., 2004)
<i>Oxidized nanotube tips for high-flux separation.</i>
Functionalized MWNT membrane (Majumder et al., 2005)
<i>Macromolecular functionalization for tunable nanofiltration</i>
Aligned DWNT (Holt., 2006)
<i>Narrowed diameter for nanofiltration and potential brackish H<sub>2</sub>O desalination</i>
Polarized and voltage-dependent wetting (Wang et al., 2007)
<i>Controllable wicks fluids for nanofluidics applications</i>
Next generation membranes:
Aligned SWNT
<i>Desalination</i>
Functionalized SWNT
<i>Functionalization for tailored selectivity and fouling resistance</i>

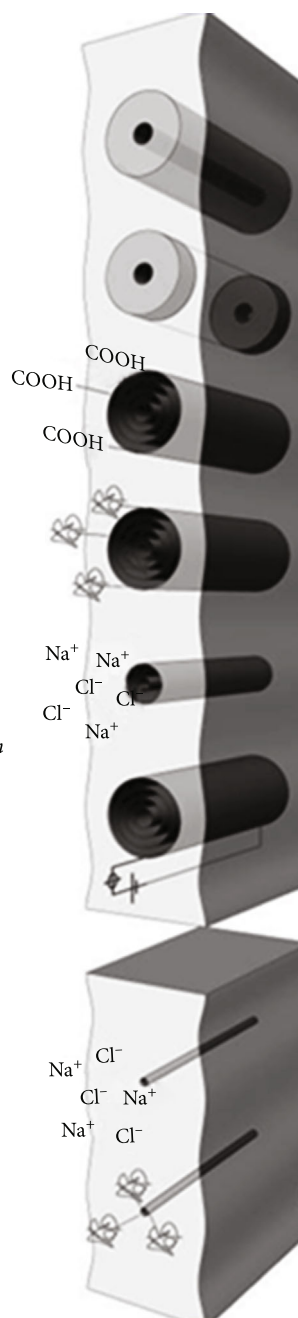


FIGURE 2: Aligned nanotube membrane development for chemical separation and water treatment.

antifouling and high flux SWNT membrane is being developed for desalination applications in the future.

Conventional fluid-flow models predict a 4–5-fold increase in the flow rate over aligned CNT membranes compared to what has already been measured [32]. It is possible to explain these high flow rates by assuming that hydrophobicity [7], nanoscale channels ([33] and smooth interior walls of CNTs) all work together to lower frictional forces on moving water molecules [11]. Molecular alignment and phase shifts are generated by the small diameter CNT confinement, which alter the behaviour of the water molecules. This alignment increases the strength of hydrogen bonds

between water molecules and forms a vapour phase barrier between the chain of water molecules and the nonpolar surface of the carbon sidewall, allowing the molecules to be separated [8].

Even nonwetting solid-fluid interfaces contradict the Hagen-Poiseuille equation's no-slip boundary condition, according to earlier research (see the discussion in paragraphs 24, 25). A larger amount of fluid can pass through small pores more quickly because the wall has less of an impact on flow when the slip length is longer; as boundary effects have less impact on flow, we can reduce our reliance on physical properties like fluid viscosity.



Nanotube pore diameter [32] is another factor to consider [13]. As a result of their hydrophobicity and atomic smoothness, carbon nanotube slip lengths have the potential to be extraordinarily long [13, 14]. Molecular dynamics simulations, for example, can be used to examine the flow properties of individual carbon nanotubes in great detail [11, 33, 34].

Process end results and physical barriers dictate the nanotube channel's input and output flow rates [10]. Membrane flow can be increased by oxidising or chemically treating CNT tips with hydrophilic functional groups [12]. It is possible to derivitize carboxylic acid groups generated during membrane formation by various chemical processes while membrane production opens nanotube ends and tips functionalization takes place [12].

CNT membrane selectivity was improved via functional group channel gating in gigantic nanotube holes. Changing the length and structure of functional groups at the ends of nanotubes allowed the team to distinguish between particles with various diameters but the same charge. In the case of Madjumder and his colleagues, steric separation strategies can reduce membrane permeability and flow by reducing the reliance of membrane selectivity on tiny changes in nanotube size. A functionalization with large streptavidin molecules, for example, entirely and reversibly eliminated membrane transport [14]. For high-flux nanotube membranes, selectivity and permeability must be equally balanced. The following is a list of their names.

Although the aforementioned membranes are important for nanofiltration, no research has proven that aligned nanotube membranes reject salt at concentrations that are required for desalination [13]. Even while charge exclusion has a small impact on salt rejection, when divalent cation strength or concentration grows, the method's efficiency plummets precipitously. Channel gated CNT membranes can no longer be separated using conventional methods due to saltwater's high ionic strength.

For sodium monoion, it varies from 0.18% to 0.358 percent according on the surrounding conditions, such as ionic strength and pH, as well as temperature. In between and the hydrated radius [14, 34], if the pore size distribution is narrowed, desalination can be accomplished using SWNT membranes with subnanometer pores or steric channel blockage. As CNT membrane design progresses, it will need to account for membrane fouling behaviour, scaling to membrane modules, and membrane production costs, amongst other things. You also need to think about the price of making a new membrane.

To manipulate small samples precisely, microfluidic systems like analytical separation or lab-on-a-chip devices need aligned CNT membranes. Charged nanotube tips become hydrophilic when a voltage is delivered across a CNT membrane that has been aligned [15]. Flow control is now possible due to the use of nanotubes and fluid wicking that have modified physicochemical interactions [12, 14, 15]. Use compression-modulated tunable-pore carbon nanotube membrane filters with variable solvent flux for molecular separation. When the CNT membrane is subjected to varying degrees of uniaxial compression, the selectivity and permeability can be dynamically altered.

#### 4. The Use of Carbon Nanoparticles in Filters

It is still difficult to make aligned CNT composite membranes since they are so fast, accurate, and customizable at the laboratory scale. Instead of employing polymers to pack the active layer in traditional reverse osmosis membranes, alternative CNT applications in nanocomposite membranes take advantage of the physical capabilities of CNTs to disturb the polymer packing.

Bonifazi et al. describe hydrophilic nanocomposite surface-coated high-flux membranes for a variety of applications [13]. It has a hydrophilic nanocomposite surface layer, a polyvinyl alcohol (PVA) midlayer, and a nonwoven microfibrillar support layer. It was found that adding MWNTs to the hydrophilic top layer increased both water permeability and the mechanical strength and durability of the coating. Water permeability was enhanced by increasing the concentration and oxidation of MWNTs, which suggests that the MWNTs disturb polymer chain packing and create nanoscale holes in the coating layer that enable flow. According to Bonifazi et al. [13], MWNTs with a high water flux have frictionless centres for 1st insertional syllable. In contrast, because aligned CNT membranes have the same pore blockage and low vertical alignment problems as unaligned ones, intratubular transfer is unlikely to significantly increase flow.

Changing the concentration of ultrafiltration membrane's oxidised microwavable nanotubes (MWNTs) improved performance, according to their results [12]. A pound and a half is the weight of it.

More MWNTs in the composite membrane increased porosity, but the thermodynamic stability dropped as the solution's viscosity decreased. Flux and solute rejection improved with the addition of oxidised MWNTs to casting solutions at increasing concentrations (up to 4 weight percent). Due to the lack of mechanistic reasons for the flow and rejection of solutes, it is difficult to develop an ideal MWNT concentration and physical-chemical property-based membrane system.

As nanoparticle technology advances, composite membranes will include higher flow rates as well as unique properties like antibacterial activity and thermal stability, all thanks to carbonaceous nanoparticles. To handle dissolved estrogenic compounds, poly(2,6-dimethyl-1,4 phenylene oxide)-fullerene composite membranes increase permeate flux by controlling heterogeneity in polymer chain packing, while also increasing the adsorption rate and capacity of the membrane.

Organic compounds are hydrophobic [14]. Using nanoparticles' unique properties in water and wastewater treatment might reduce risks while increasing efficiency, provided that nanomaterial immobilisation can be demonstrated across the membrane lifespan.

Regenerative hybrid ceramic filters can use tiny-wavelength nanotubes (SWNTs) because of their small diameter, huge surface area, thermal conductivity, and porous structure. There has been recent research showing that a SWNT filter with a high permeance can effectively remove bacterial and viral pathogens from water, expanding on previous findings of MWNT filter efficacy in bacterial

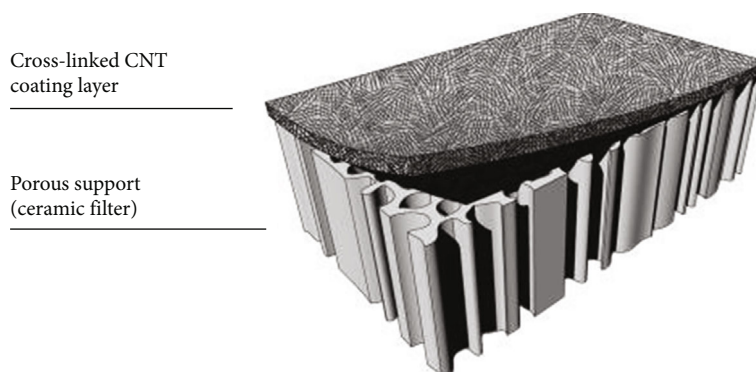


FIGURE 3: Hybrid CNT filter schematic illustration. Cross-linked CNT filtration on a porous ceramic substrate forms the basis of a durable water purification system that is also regenerative.

removal [18, 19]. Viral elimination is inversely related to filter thickness, indicating a depth-filtration process, while bacterial retention and inactivation take place on the filter's surface. In light of this study, a high-temperature-resistant SWNT-ceramic hybrid filter that may be reused in water treatment applications at the point of use is now possible to build (Figure 3). We still have a long way to go before this technology is commonly used in the purification of drinking water.

To some extent, the difficulty of immobilising nanotubes in air filtration has been overcome by synthesising MWNTs directly on the surface of a typical metal filter [21]. High-temperature hydrogen gas reduces the metal filter, forming catalytic sites for nanotube development. Containment of flow rate during nanotube synthesis allows simple control of nanotube morphology and filter collecting efficiency. Further refining of the filter by nanotube functionalization pathways may enable the removal of specific micropollutants from air streams, even if the removal efficiencies for inert NaCl particles have been quantified. For example, the effectiveness of oxidised MWNTs in cigarette filters for nicotine and tar adsorption has been studied [22].

#### 4.1. Carbonaceous Nanomaterials as Antimicrobial Agents.

Fullerenes and nanotubes have spawned a slew of new environmental uses while also raising concerns among toxicologists and environmental scientists due to their unique features and nanoscale dimensions. There is still investigation into the particular pathways by which antimicrobial activity works, even though it is known that toxicity can be modified by physical-chemical and structural features such as surface chemistry, functional group density, length, and residual catalyst contamination. This new antimicrobial knowledge could be used in environmental and human health applications, say several researchers. Nanomaterials may have use in water disinfection [34], medicinal therapy, antimicrobial surface coatings [21], and microbiology laboratory techniques [21, 22].

Pathogens can be effectively controlled by intentionally disrupting cell membranes. Biological factors do not promote antibiotic resistance, and membrane disrupting drugs are broad spectrum antibiotics. Researchers recently discov-

ered that direct interaction with SWNTs caused *Escherichia coli* K12 toxicity, suggesting that membrane rupture is the primary mechanism of inactivation [17, 35]. Biofilm colonisation and device failure in drinking water systems, medical implant devices, and other submerged surfaces can be solved with novel antimicrobial surface coatings that take use of bacteria's natural vulnerability to CNTs. There is continuing research into the toxicity of CNTs to various microbial ecosystems [23].

Antimicrobial and antiviral nanoparticles are being investigated by a number of research groups for use in water treatment and distribution systems. Removing and neutralising microorganisms from SWNT hybrid filters has also been discussed previously [34]. For antibacterial Ag nanoparticles [16], CNT scaffolds have also been proposed, as have TiO<sub>2</sub> and other semiconducting photocatalysts [24].

In water and wastewater treatment, pathogen inactivation and nC-60 (210) may also be relevant if obstacles to nanomaterial immobilisation and separation are overcome [35]. According to current theories, fullerols' antiviral properties are due to their ability to generate singlet oxygen under UV light or superoxide under UV light and an electron-donating molecule [18]. Finally, across a variety of environmental circumstances, stable nC-60 suspensions displayed significant antibacterial action against physiologically different bacteria [35].

#### 4.2. Nanomaterials Made of Carbonaceous Compounds for Environmental Sensing.

A wide range of challenges of all kinds are faced daily by environmental scientists, engineers, and policymakers. There are various factors that determine how harmful an agent is, including the amount of water it pollutes and the number of people it affects (ppt). A lot of individuals are sceptical about nanotechnology's capacity to help solve these major environmental problems.

In contrast, environmental sensing is a nanotechnology application that has the potential to close this gap. In order to build prediction models and make policy decisions for the future, increasing numbers of networked sensing devices are currently being used in research. As part of the WATERS network, which is a sensor network linking environmental observatories, models, and predictions for water quality,

quantity, are being developed [35]. To achieve this level of scalability and forecasting, you will need a variety of sensors that are both precise and adaptable.

There have been a number of recent critical assessments that connect readers to conversations about the advantages of CNT-based sensors over traditional sensor systems. CNTs are employed in a wide range of sensor applications due to their excellent electrical conductivity and chemical stability, as well as their high surface area and mechanical stiffness. The use of CNTs in thermal, optical, and stress and strain sensors are in addition to chemical and biological sensors [25]. MWNT arrays produced on a SiO<sub>2</sub> substrate can also be employed as anodes in gas detection ionisation sensors [26]. To make small, battery-operated sensors, researchers are turning to nanotubes with sharp edges. When the sample is exposed to an electric field, it disintegrates, leaving behind a unique fingerprint for each gaseous analyte.

In the field of sensing, the introduction of CNT nanowire sensors is a game changer. Adsorption of charged species on CNT surfaces links changes in analyte concentration to oscillations in the current flow. Analogous, the electrical resistance of semiconducting SWNTs altered by three orders of magnitude in seconds following exposure to part per million concentrations of NO<sub>2</sub> or NH<sub>3</sub> in experiments conducted by Shinohara et al. [17]. SWNTs offer quick response times, low detection limits, and high sensitivity due to their vast and totally exposed surface area.

Much may be gained by utilising nanowire sensor technology to detect chemicals and biologics that are not attracted to carbon nanotubes [17]. When a substance is covalently or supramolecularly functionalized, it can be modified in a variety of ways. Wang [18, 33] and others have studied CNT biosensors extensively for use in environmental monitoring systems. Monitoring of health and safety, infrastructure management, chemical and material efficiency in industry, and cost-effective regulatory platforms are examples of other environmental uses for these technologies.

In addition to detecting pathogens, biosensor platform research is aimed at keeping tabs on environmental microbiology. It is possible to detect nucleic acid or protein targets directly on the CNT electrode array surface without the need of labels [20]. You can enhance the performance of signal channels during recognition and transduction. Several of these technologies have detection limits of attomolar (10<sup>-18</sup> M) or zeptomolar (10<sup>-21</sup> M), opening the door to direct detection approaches rather than the present practise of PCR-mediated amplification and analysis. These nanobased sensor networks can be used in a variety of ways, including speeding up the response to microbial outbreaks in water systems, expanding monitoring of subterranean biodegradation, and capturing bacterial evolution in response to perturbations.

*4.3. Carbon-Based Nanomaterials for Solar and Wind Energy Production.* Between 2004 and 2030, global commercialised energy consumption is expected to rise by 57% [22]. In addition, the use of fossil fuels, energy transit over national borders, and process water consumption are all increasing in lockstep with this trend. Even if coal continues to be the

major market replacement, future developments in renewable energy sources such as solar, wind, bio, or low-grade heat sources would need multidisciplinary and cross-national collaboration.

The vast bulk of these advancements, however, will be to secondary components in renewable energy applications that employ nanoparticles and nanocomposites. The use of carbon nanotube (CNT) anodes in nuclear power plant radiation counters may improve the counters' sensitivity and spatial resolution [23]. The usage of low-grade heat via an osmotic heat engine could be enabled by nanotube membranes with symmetrical alignment [24]. Wind turbines that use stronger, lighter materials may benefit structurally as well [25].

Solar energy applications have the greatest promise for significant advances in carbonaceous nanomaterials. Affordability, material availability (such as indium), and device flexibility are now stifling the expansion of the photovoltaic and photoelectrochemical energy industries [26].

Carbon nanotubes and fullerenes are frequently employed in solar energy conversion and storage because they are low-cost, micrometer-scale materials with superior electrical and optical capabilities [27, 28]. Researchers have long been interested in the use of carbonaceous nanomaterials for solar energy collection, storage, and conversion. In order to highlight the enabling function of nanoscale molecular manipulation, this article critically examines only a few of these emerging technologies.

Adsorbed photons are transformed to an electrical charge and used to power an external circuit using photovoltaic systems. Innovative organic solar cell topologies promise more efficiency and flexibility in the future when compared to typical inorganic silicon-based photocurrent production systems [28]. Electron and hole pairs with a strong connection are used.

Short exciton diffusion lengths [26], as well as acceptor-donor layer thickness, are advantageous in organic solar cells [26]. To solve these challenges, the active layer of organic photovoltaic systems uses bulk heterojunction architecture [18, 31]. Donor and acceptor materials should have chemical parameters such as phase separation and segregation length that are both equivalent to the excitation diffusion time as a rule of thumb [18].

Despite their thickness limitations, the polymeric fullerene bulk heterojunction donor-acceptor materials are inexpensive and have excellent charge separation capabilities [26]. Because of their high electron acceptivity, good charge transport efficiency, and dense crystal packing features, organic fullerenes are the most often used solar cell acceptor materials [18]. Fullerene molecules' tunable optical, electrical, and chemical capabilities have been used to optimise solar devices. In thin-film casting, functional groups can be utilised to improve fullerene miscibility while preserving the optical properties of the polymer-fullerene dyad [23]. Molecular changes enhance the HOMO-LUMO energy interaction with the donor polymer, extend the duration of the charge separated state, promote visible light adsorption, and produce thermodynamically favourable heterojunction topologies (41). CNTs and fullerenes have also been used

as chromophores in organic-in-organic hybrid photovoltaic cells and dye-sensitized solar cells due to their optical activity (DSSC).

Carbon-based nanomaterials are used as a transparent conducting anode in various solar systems. When it comes to solar cell efficiency, high-transmittance anodes aid to boost active layer excitation while low-sheet resistance anodes help to reduce power loss during manufacturing. Indium-tin oxide, the typical material of choice, is rare in nature and has some chemical and optical constraints (48). SWNT thin films have been used to substitute anodes that are low-cost, transparent, highly conductive, and physically flexible. Despite the fact that great efficiencies have been achieved, the separation of semiconducting and metallic SWNTs is challenging.

Semiconducting materials in photoelectrochemical cells deliver charge to a counter electrode in contact with an electrolyte solution redox pair (45). Charge separation occurs when semiconducting carbon nanotubes are subjected to UV radiation, resulting in charge transfer to a solution phase reactant. Carbon nanotubes (CNTs) that are semiconducting (35, 47). Even when exploiting the photoactive properties of CNTs directly in photoelectrochemical cells, semiconducting materials such as  $\text{TiO}_2$  are preferable catalytic agents. In these nanoscale inorganics, however, significant charge recombination occurs as the free electron migrates to the electrode surface (50). It has also been suggested that CNT-based conductive scaffolds be used to limit charge recombination rates at the electrode. The electrode's strong conductivity and seamless contacts with the SWNTs allow for less charge recombination. Making monochiral nanotubes is another technique to increase the performance of CNT scaffolding.

Photochemically produced hydrogen is used to power PEM fuel cells, which generate electricity without emitting any waste into the atmosphere. An anode for hydrogen molecule dissociation, an electrolyte spacer, and an oxygen reduction cathode are the three fundamental components of a PEM battery [27]. Though carbon particles have typically been used as a porous scaffold in electrode designs (32, 233), ordered carbon nanostructures can increase fuel cell voltage output (258, 261). Changes to the anode to CNTs improve charge transmission [21] and improve the triple phase contact layer between the carbon electrode and the noble metal catalyst (proton conductor). The low number of dangling bonds in CNTs improves corrosion resistance at the highly acidic cathode, while the porous structure of the CNT mesh electrodes ensures gas diffusivity and a water removal pathway. It was demonstrated that utilizing SWNTs as a scaffolding agent reduced platinum recrystallization rates, increasing fuel cell lifespan. Finally, the structural and mechanical properties of carbon nanotubes enable the construction of freestanding fuel cell electrodes with increased conductivity and ease of manufacture over nanotubes cast on carbon paper or other support materials.

Energy storage technologies, in addition to renewable energy sources, must be both efficient and cost-effective. Hydrogen storage devices with substantial storage capacities

and rapid desorption at mild temperature rises are important to the potential of the hydrogen economy. Although carbon-based nanomaterials have received a lot of attention as a potential missing link in the development of a reliable and cost-effective hydrogen storage system, current research indicates that existing carbon nanostructures do not meet DOE targets for hydrogen storage volumetric or gravimetric density. A variety of hypothetical carbon nanoparticle morphologies have also been investigated, but none of the configurations provided putative storage capacities that met DOE requirements. Metal oxide nanoparticles with high hydrogen affinities will most likely be scaffolded with carbon nanotubes (CNTs) as a binding agent.

### Data Availability

The data used to support the findings of this study are included within the article. Should further data or information be required, these are available from the corresponding author upon request.

### Disclosure

It was performed as a part of the Employment of School of Chemical Engineering, Jimma Institute of Technology, Jimma University, Jimma, Oromia, Ethiopia.

### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

### Acknowledgments

The authors thank KSRM College of Engineering, Kadapa, Vignans Nirula Institute of Technology & Science for women, Guntur, and Jimma Institute of Technology, Jimma University, Jimma, Oromia, Ethiopia for providing characterization supports to complete this research work.

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