Scholars Academic Journal of Biosciences
Abbreviated Key Title: Sch Acad J Biosci
ISSN 2347-9515 (Print) | ISSN 2321-6883 (Online)
Journal homepage: https://saspublishers.com

OPEN ACCESS

Chemistry

Carbon Nanotubes as Multifunctional Tools Advancing Batteries and Catalysis for Sustainable Solutions

Fiza Zafar[1*], Muhammad Abid Sultan[2], Amna Nasir[1], Asna Fatima Kiani[3], Mohsin Saleem Ghouri[4], Saadia Ahmad[5], Muhammad Yousaf[6], Uzair Ahmad[7], Muhammad Saqib Murad[1]

[1]Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan
[2]Department of Chemistry, Government College University Faisalabad, Pakistan
[3]School of Chemistry, University of Edinburgh, United Kingdom
[4]Department of Chemistry, Government Murray Graduate College, Sialkot, Punjab Pakistan
[5]Department of Chemistry, Beijing University of Chemical Technology, China
[6]Department of Physics, University of Agriculture Faisalabad, Punjab Pakistan
[7]Institute of Chemical Sciences Bahauddin Zakariya University Multan

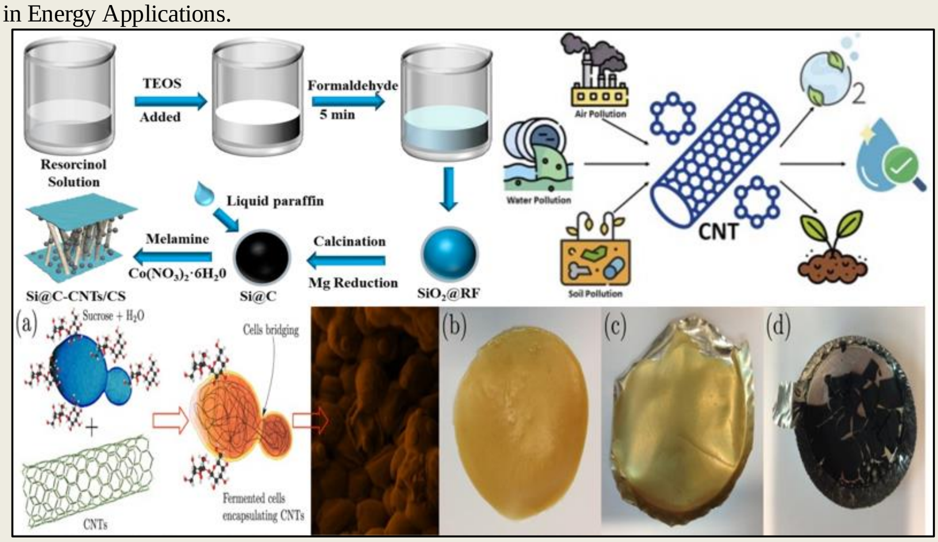
DOI: https://doi.org/10.36347/sajb.2025.v13i01.019 | **Received:** 06.01.2024 | **Accepted:** 25.01.2025 | **Published:** 28.01.2025

***Corresponding author:** Fiza Zafar
Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan

Abstract **Review Article**

With a focus on their application in batteries and catalytic processes for sustainable solutions, this review article explores the revolutionary potential of carbon nanotubes (CNTs) as multifunctional materials that are advancing the fields of energy storage and catalysis. Their remarkable mechanical, electrical, and thermal properties have attracted considerable attention due to their potential to revolutionize energy storage devices such as lithium-ion batteries, supercapacitors, and emerging solid-state technologies. The high surface area, conductivity, and structural versatility of CNTs enable them to improve charge capacity, cycling stability, and efficiency in battery systems. Additionally, CNTs exhibit remarkable catalytic properties, particularly in green chemistry, where they act as active catalysts in energy conversion processes such as hydrogen production, CO2, and decrease and conversion of biomass. The review highlights recent developments in CNT-based materials, the synthesis methods that maximize their performance, and their incorporation into energy systems for sustainable development. It also covers the difficulties in scaling up CNT-based technologies and the potential solutions to these problems, paving the way for their use in large-scale industrial settings. In the end, this analysis underscores the inspiring potential of carbon nanotubes (CNTs) in propelling the transition to a more sustainable energy future, highlighting their versatility in energy storage and catalytic applications.

Keywords: Carbon Nanotubes (CNTs), Multifunctional Nanomaterials, Energy Storage, Lithium-Ion Batteries, Advanced Battery Technology, Supercapacitors, Hydrogen Evolution Reaction (HER), Oxygen Reduction Reaction (ORR), Fuel Cell Technology, Nanotechnology in Energy Applications.



Graphical Abstract

Citation: Fiza Zafar, Muhammad Abid Sultan, Amna Nasir, Asna Fatima Kiani, Mohsin Saleem Ghouri, Saadia Ahmad, Muhammad Yousaf, Uzair Ahmad, Muhammad Saqib Murad. Carbon Nanotubes as Multifunctional Tools Advancing Batteries and Catalysis for Sustainable Solutions. Sch Acad J Biosci, 2025 Jan 13(1): 190-202.

INTRODUCTION

The innovative work of scientists investigating the atomic structures of carbon is the origin of carbon nanotubes (CNTs), a revolutionary advancement in nanotechnology (Yang *et al*., 2015). Because of their exceptional structural, electrical, and mechanical qualities, carbon nanotubes (CNTs) immediately attracted international interest after being first seen in 1991 by Sumio Iijima using transmission electron microscopy. Single-walled (SWCNTs) and multi-walled (MWCNTs) are the two main types of cylindrical molecules, which are made up of one or more graphene sheets coiled into seamless tubes (Dariyal *et al*., 2023). However, the conceptual work on graphene, particularly in the middle of the 20th century, when scientists started to realize the possibilities of two-dimensional carbon structures, is much older than the theoretical underpinnings of carbon nanotubes. The remarkable strength, electrical conductivity, thermal stability, and high surface area-to-volume ratio of carbon nanotubes (CNTs) have elevated them to the forefront of material research and earned them the moniker "materials of the future (Stachowska *et al*., 2021). Advances in synthesis methods like chemical vapor deposition (CVD) and arc discharge have made it possible to produce carbon nanotubes (CNTs) in large quantities throughout the years, opening the door for their use in a variety of industries, including electronics, medicine, and environmental cleanup. This announcement signals the beginning of multifunctional carbon nanotubes (CNTs) as scientists continue to explore their potential to transform businesses and solve global issues through creative uses (Rao *et al*., 2018).

Nanomaterials' distinct physicochemical characteristics, such as their large surface area, adjustable electronic structures, and capacity to support intricate reaction pathways, have made them an attractive platform for energy and catalysis applications. With their increased charge storage capacity, quicker charging cycles, and longer lifespan, nanostructured materials such as metal oxides, graphene, and carbon nanotubes have transformed battery and supercapacitor technology in the energy storage industry. These advancements reassure us about the progress in sustainable solutions. Similarly, by improving light absorption, charge separation, and catalytic activity, nanoparticles and nanostructured semiconductors play crucial roles in energy conversion systems like fuel cells and solar cells. Nanomaterials serve as extremely effective catalysts or catalyst supports in catalysis, allowing for notable decreases in reaction durations and energy inputs while simultaneously boosting reaction yields. Their size-dependent characteristics, such as defect engineering in two-dimensional materials or quantum effects in metal nanoparticles, provide exact control over catalytic activity and selectivity. Furthermore, by combining complementary qualities like improved stability and synergistic activity, developments in heterostructure and hybrid nanomaterials have further increased their usefulness and made them perfect for intricate procedures like CO2 reduction, water splitting, and ammonia synthesis. The capacity of nanomaterials to facilitate cleaner processes and renewable energy solutions highlights their crucial role in tackling energy and environmental concerns as sustainability gains international attention.

A wide range of initiatives are included in sustainability-driven innovation, which aims to create solutions that strike a balance between social well-being, environmental conservation, and economic growth. It has an impact on how goods are made, procedures are optimized, and services are provided in a variety of industries, including manufacturing, energy, healthcare, and agriculture. This strategy places a high priority on incorporating sustainable practices into innovative processes, such as cutting waste, using renewable resources, and lowering carbon footprints. The importance of sustainability-driven innovation cannot be overstated, as it is crucial to tackle the pressing global issues of resource scarcity, social injustice, and climate change. Beyond its positive effects on the environment, sustainability-driven innovation generates new revenue streams, giving companies a competitive edge and resilience while encouraging moral behavior that aligns with customer values. This paradigm aims to develop services, goods, and systems that satisfy current demands without endangering the capacity of future generations to satisfy their own. The goal of integrating sustainability into innovation initiatives is to provide fair access to resources, foster responsible consumption, and foster stakeholder engagement. To put it simply, innovation driven by sustainability is a revolutionary route to a more sustainable future in which social development, ecological preservation, and economic growth coexist together.

Structural and Functional Attributes of Carbon Nanotubes

A fundamental component of material science and nanotechnology, carbon nanotubes (CNTs) have remarkable structural and functional properties (Rathinavel *et al*., 2021). CNTs are cylindrical carbon molecules made of rolled graphene sheets. They are categorized as either single-walled carbon nanotubes (SWCNTs) or multi-walled carbon nanotubes (MWCNTs), each of which has unique characteristics. While MWCNTs, which are made up of several concentric layers, offer increased mechanical strength and endurance, SWCNTs, with their single-layered walls, offer higher electrical conductivity and flexibility. By adding chemical groups to their surface, CNTs may be functionalized, which further customizes their characteristics for particular uses like boosting interactions with chemical or biological systems or increasing dispersibility in solvents (Sabet *et al*., 2024). Functionally, CNTs are perfect for a variety of applications, including electronics, energy storage, sensors, and drug delivery systems, because of their excellent electrical conductivity, remarkable thermal stability, and huge surface area. They may be used as reinforcements in composite materials due to their mechanical strength, which is an order of magnitude higher than that of steel in terms of tensile strength. Additionally, their versatility in tackling problems across a variety of technological fields is highlighted by their ability to fine-tune their electrical and mechanical properties through controlled synthesis and functionalization, which opens the door to innovations in nanoelectronics, catalysis, and biomedicine (Weerarathna *et al*., 2024).

Redefining Carbon Nanotubes for a Net-Zero Future

A paradigm change from considering carbon nanotubes (CNTs) as just adaptable materials to seeing them as game-changing answers to the green energy issue is required to redefine CNTs for a net-zero future (Nawaz *et al*., 2024). CNTs have been essential in developing energy storage technologies like lithium-sulfur batteries and supercapacitors because of their remarkable electrical conductivity, thermal stability, and large surface area. These technologies offer improved performance while promoting sustainable energy objectives. Beyond storage, carbon nanotubes (CNTs) are proving to be invaluable in catalysis, where their adjustable characteristics allow for the effective synthesis of hydrogen through CO2 reduction and water-splitting processes, which is essential for the switch to renewable energy sources (Yan *et al.,* 2015). Additionally, by supporting the development of low-energy and recyclable production techniques, CNTs are lowering waste and its negative effects on the environment, thus opening the door for circular economies in materials research. Their use in high-strength, lightweight composites for the building and transportation industries lowers carbon footprints and energy use, supporting decarbonization goals. These nanomaterials are positioned to close the gap between innovation and sustainability, speeding up the world's shift to a net-zero future as scientists improve CNT synthesis methods to reduce their environmental impact. This reinterpretation emphasizes CNTs as essential facilitators of systemic change in tackling climate issues rather than just as multifunctional materials (Shukla *et al*., 2024).

CNTs as Self-Evolving Materials

Carbon nanotubes (CNTs) are emerging as self-evolving materials due to their remarkable ability to adapt, heal, and optimize under various conditions (Gupta *et al*., 2022). These dynamic materials exhibit adaptive behavior under operating conditions, enabling them to respond to environmental changes such as temperature, pressure, and chemical exposure. Adaptive CNT materials can adjust their mechanical, thermal, and electrical properties in real time, making them invaluable for advanced applications in aerospace, electronics, and biomedicine. A significant breakthrough in this field is the development of programmable CNTs, where their structure and functionality can be tuned to achieve real-time optimization in energy systems. For example, by dispersing current or reducing heat hotspots while in use, CNT-based electrodes in energy storage devices such as supercapacitors and batteries can reorganize themselves to optimize energy efficiency and lifetime (Kothandam *et al*., 2023). Furthermore, CNTs are being developed with self-healing properties, which will enable them to fix damage or structural flaws automatically. Mechanisms like thermally induced polymerization or the addition of reversible chemical bonds provide this self-healing capability, guaranteeing long-term performance and increasing material longevity. Additionally, self-reconfiguring CNT designs are more adaptable for multipurpose applications because they may dynamically rearrange their internal structures in response to stress or outside stimuli. All of these developments put carbon nanotubes (CNTs) at the forefront of creating materials that are tough, intelligent, and self-evolving for the upcoming generation of technology (Nepal *et al*., 2023).

Energy Storage Reimagined: CNTs in Next-Gen Paradigms

CNTs in Beyond-Traditional Chemistries

Particularly in the field of non-traditional ion-based energy storage systems like fluoride-ion and chloride-ion batteries, carbon nanotubes (CNTs) have become revolutionary materials in non-traditional chemistries (Karkera *et al*., 2021). They are perfect candidates for enhancing the performance of these innovative battery chemistries due to their distinct structural and electronic characteristics, which include excellent electrical conductivity, a huge surface area, and remarkable mechanical strength. CNTs operate as structural frameworks and conductive additions in fluoride-ion batteries (FIBs) to lessen the problems caused by the extreme corrosiveness and reactivity of fluoride ions. By allowing for volume variations during charge-discharge operations, they increase cycling stability, stabilize electrode interfaces, and improve ion transport (Li *et al*., 2021). Likewise, CNTs are essential for facilitating the reversible electrochemical reactions of chloride ions in chloride-ion batteries (CIBs), which frequently experience slow kinetics and the development of dendrites. In addition to offering strong electron routes, CNTs serve as hosts for chloride ions, improving electrode stability and ion transport. CNTs are pushing the limits of the periodic table in energy storage by utilizing these properties, opening the door to the creation of systems that make use of unusual anions that have high energy densities, are widely available, and have less of an adverse effect on the environment. By combining CNTs with unconventional chemistries, next-generation batteries can advance beyond the limitations of lithium-ion technology (Zhang *et al*., 2018).

CNTs in Biobatteries and Enzyme-Powered Systems

The remarkable electrical conductivity, large surface area, and biocompatibility of carbon nanotubes

(CNTs) have made them a game-changing material in the development of bio-hybrid energy systems, especially biobatteries and enzyme-powered systems (Afroz *et al*., 2021). CNTs are effective mediators of electron transfer in biobatteries, allowing electrons to move directly between enzymes or microbes and electrodes, increasing power production. The stability and catalytic performance of the biocatalysts are increased by their structural characteristics, which enable the immobilization of bioactive molecules and redox enzymes. CNTs are frequently functionalized with certain groups for enzyme-powered systems in order to enhance electron transfer and enzyme binding rates, leading to more reliable and effective bio-electrochemical systems. Furthermore, CNTs play a key role in microbial fuel cells (MFCs), where they improve the communication between bacterial cells and electrodes and make it easier for electrons to go from the metabolic activities of the microorganisms to the electrode surface (Yazdi *et al*., 2016). Because of this property, CNTs are extremely advantageous for decentralized energy generation, especially in environments with limited resources or off the grid. Additionally, their integration with electrode materials creates a conductive and porous network that promotes biofilm development and metabolism, enhancing system performance as a whole. By fusing the benefits of cutting-edge nanomaterials with the potential for renewable energy, the incorporation of CNTs into bio-hybrid systems opens the door for scalable and sustainable energy solutions (Sharfstein *et al*., 2022).

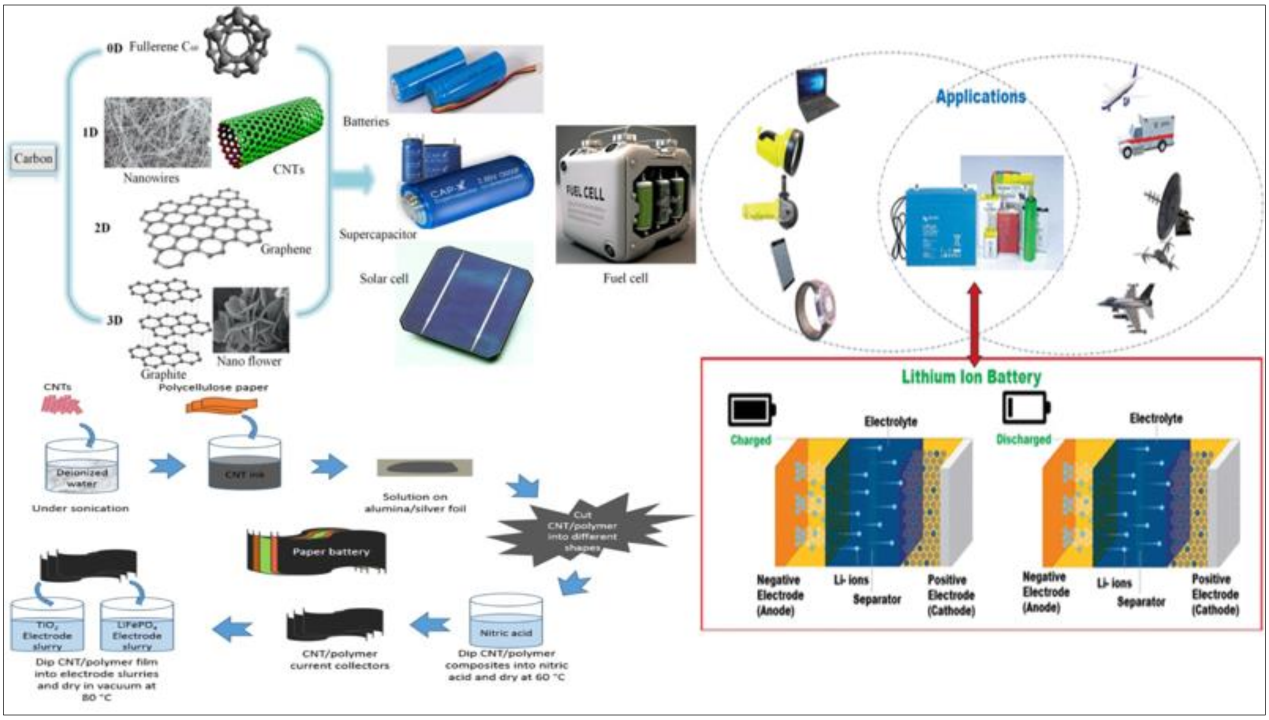


Fig. 1: Energy Storage Reimagined CNTs in Next-Gen Paradigms, CNTs in Beyond-Traditional Chemistries, CNTs in Biobatteries and Enzyme-Powered Systems

Carbon Nanotubes as Atomic Precision Catalysts CNTs in Single-Atom Catalysis (SAC)

Because of their large surface area, superior conductivity, and strong mechanical characteristics, carbon nanotubes (CNTs) are essential to the development of single-atom catalysis (SAC) because they provide the perfect platform for attaching individual metal atoms (Singh *et al*., 2021). The catalytic effectiveness is greatly increased by immobilizing single metal atoms onto the functionalized surfaces or defect sites of carbon nanotubes (CNTs). This is because the isolated atoms optimize active site-use while decreasing metal waste. Outstanding catalytic performance is made possible by this special arrangement, which permits precise electrical contact between the metal atoms and the CNT framework. In CO_2 reduction processes, for example, single-atom catalysts based on carbon nanotubes (CNTs) have shown exceptional efficiency, converting CO_2 ultra-selectively into compounds with added value like methanol and hydrocarbons. The CNTs' fine-tuned electronic structure and local coordination environment, which stabilize reaction intermediates and reduce the energy barriers for important reaction routes, are the source of this selectivity (Chen *et al*., 2022). Similar to this, CNT-supported single-atom catalysts in ammonia synthesis maximize the adsorption and activation of nitrogen molecules, a crucial stage in the process, allowing for high activity in moderate circumstances. The combination of carbon nanotubes with single-atom catalysts opens the door to revolutionary developments in green chemistry, providing long-term answers to environmental and energy problems (Habib *et al*., 2023).

CNTs as Catalytic Nano-Reactors

In nanotechnology, carbon nanotubes (CNTs) have become revolutionary instruments, especially as catalytic nano-reactors (Isola *et al*., 2022). They are the perfect setting for restricted catalytic reactions because of their distinctive hollow tubular form, large surface area, and remarkable temperature and chemical resilience. In contrast to bulk-phase catalysis, confined catalysis is made possible by carbon nanotubes (CNTs), which offer nanoscale chambers where reactant molecules are spatially constrained. This results in improved reaction selectivity, faster reaction rates, and distinct product distributions. By avoiding agglomeration and providing uniform dispersion, the graphitic walls of carbon nanotubes (CNTs) can stabilize catalytic species, such as metal nanoparticles or enzymes. Furthermore, CNTs are flexible platforms for creating unique nano-reactors due to their adjustable electronic characteristics, which enable accurate catalytic activity control. CNTs' promise in real-time molecule assembly has been further revealed via time-resolved catalysis (Chen *et al*., 2024). The manufacture of complicated compounds or sophisticated materials is made possible by CNTs' ability to enclose reactants and serve as controlled environments for progressive chemical reactions. This confinement effect favors particular reaction pathways by improving molecular contacts and producing distinct electronic and steric environments. These developments are especially encouraging in domains like medicine synthesis and renewable energy applications, where accuracy and efficiency are crucial, as well as green chemistry, where CNTs may limit byproducts and lower energy usage (Islam *et al*., 2024).

Molecular Engineering of CNT Catalysts

A potential method for improving catalytic performance, particularly in areas like environmental remediation and biocatalysis, is the molecular engineering of carbon nanotube (CNT) catalysts (Upadhyayula *et al*., 2010). One of the novel approaches is to hybridize CNTs with proteins and enzymes to produce artificial biocatalysts, which combine the efficiency and selectivity of biological molecules with the special qualities of CNTs, such as their large surface area and electrical conductivity. In applications like wastewater treatment and biofuel generation, this synergy enables more efficient catalytic processes. In addition to promoting electron transfer in redox processes, the stable and conductive framework that the CNTs offer aids in the immobilization of enzymes, avoiding denaturation and increasing their reusability. The application of molecularly imprinted CNTs, which are made to have certain binding properties, is another innovative advancement (Chen *et al*., 2011). These CNTs achieve great selectivity for specific molecules by template-assisted polymerization, guaranteeing accurate reactant targeting in intricate reaction settings. By simulating the inherent catalytic specificity of enzymes, this method makes it possible to create extremely effective, customized catalysts for industrial processes. By offering effective, adaptable solutions that function in mild environments and have a high catalytic turnover, the incorporation of these technologies into CNT catalysts has the potential to completely transform fields like biosensing, green chemistry, and sustainable energy (Chadha *et al*., 2022).

Table 1: Carbon Nanotubes as Atomic Precision Catalysts

Category	Description	Applications	Key Advantages	Challenges	Reference
CNTs in Single-Atom Catalysis (SAC) Anchoring individual metal atoms	Carbon nanotubes (CNTs) act as supports to stabilize single metal atoms, ensuring high dispersion and accessibility for catalytic processes.	Ultra-selective CO_2 reduction to useful hydrocarbons, ammonia synthesis, and hydrogen evolution reactions.	Maximized catalytic efficiency, minimal metal usage, and reduced side reactions.	Stability of single-atom catalysts under reaction conditions and scalability of synthesis techniques.	Chen *et al*., 2019
Single-atom CNTs for CO_2 reduction	Single-atom catalysts (SACs) anchored on CNTs offer superior selectivity and activity for CO_2 reduction, converting it into value-added chemicals.	Production of fuels and chemicals (e.g., methanol, ethanol) from CO_2, contributing to carbon capture and utilization strategies.	High atom efficiency, tailored electronic properties, and potential for industrial-scale CO_2 valorization.	Design of catalysts with durability and cost-effective regeneration.	Verma *et al*., 2023
CNTs as Catalytic Nano-Reactors	CNTs provide a confined environment, functioning as	Time-resolved catalysis, such as controlled polymerization or	Enhanced reaction control, prevention of side reactions, and unique	Achieving precise control over reactant and	Khlobystov *et al*., 2011

Confined catalysis	nanoscale reactors that enhance reaction selectivity and efficiency.	molecular assembly reactions.	electronic effects from CNTs.	product transport within CNTs.	
Real-time molecular assembly	CNTs enable time-resolved catalytic processes, allowing for dynamic observation and optimization of molecular assembly pathways.	Applications in drug synthesis, nanostructured materials, and high-performance polymers.	Capability for real-time monitoring and optimization of catalytic pathways.	Development of in situ analytical techniques for confined reaction monitoring.	Chen *et al*., 2024
Molecular Engineering of CNT Catalysts Hybridizing CNTs with enzymes	CNTs are functionalized with enzymes or proteins to create artificial biocatalysts for specific chemical reactions.	Biomimetic catalysis for pharmaceuticals, green chemistry processes, and biofuel production.	Enhanced stability and reusability of enzymes, precise reactant targeting, and environmentally friendly methods.	Compatibility of enzymes with CNTs and preservation of enzymatic activity under reaction conditions.	Aggarwal *et al*., 2023
Molecularly imprinted CNTs	CNTs are engineered with molecular imprints to target and catalyze specific reactants selectively.	Selective catalysis for fine chemicals, environmental remediation, and food safety applications.	High specificity, potential for recycling catalysts, and versatility in targeting diverse reactants.	Challenges in creating robust and reproducible molecular imprints on CNT surfaces.	Li *et al*., 2024

CNTs in the Era of Decentralized and Off-Grid Solutions

Energy Sovereignty with CNT-enabled Micro-Storage

The idea of energy sovereignty enabling people and communities to produce, store, and control their own energy needs is becoming more popular as carbon nanotube (CNT)-enabled micro-storage devices are included (Jha *et al*., 2020). Compact, effective, and high-capacity systems made possible by carbon nanotubes (CNTs), which are renowned for their remarkable electrical conductivity, mechanical strength, and large surface area, are transforming energy storage technology. CNT-enabled micro-storage devices can be the foundation of localized energy independence in self-powered houses and personal energy grids by enabling the smooth capture and storage of renewable energy from sources such as wind turbines and solar panels (Hashem *et al*., 2023). These technologies greatly improve energy security by guaranteeing a steady electricity supply even during periods of high demand or outages. Additionally, portable energy solutions for off-grid areas, where conventional energy infrastructure is not available, are about to transform thanks to CNT-based energy storage. CNT-enabled batteries and capacitors are strong and lightweight and provide the flexibility required to power tiny appliances and other equipment. They are a sustainable substitute for large, ecologically damaging systems. CNT-based micro-storage encourages both environmental sustainability and economic empowerment for marginalized communities by facilitating localized energy solutions, which is in line with the worldwide movement toward greener, more resilient energy ecosystems. This invention paves the door for universal energy autonomy by bridging the gap between state-of-the-art nanotechnology and practical energy issues (Betz *et al*., 2023).

CNTs in Localized Catalysis for Green Chemistry

In localized catalysis for green chemistry, carbon nanotubes (CNTs) are becoming revolutionary materials that promote sustainability and decentralized chemical synthesis (Chakrabartty *et al*., 2022). They are perfect catalysts or catalyst supports in chemical processes that demand accuracy and efficiency because of their special structural, electrical, and thermal characteristics. CNTs operate as high-surface-area platforms in localized catalysis, increasing reaction rates, functionalizing active catalytic sites, and improving selectivity under mild circumstances. This feature is especially helpful in isolated and rural locations where it is not feasible to produce chemicals on a big scale. Small-scale on-demand synthesis of necessary chemicals, such as fuels, fertilizers, and medications, is made possible by incorporating carbon nanotubes (CNTs) into microreactors. For instance, CNT-supported catalysts can facilitate hydrogen production, CO_2 conversion into methanol, or ammonia synthesis through greener, energy-efficient pathways, reducing dependency on centralized industrial facilities (Mondal *et al*., 2021). The thermal and electrical conductivity of CNTs also enables efficient heat and electron transfer in catalytic systems, minimizing energy losses and further contributing to sustainability. These reactors can operate with renewable energy sources like solar or biomass-derived power, aligning with the principles of green chemistry to reduce waste and emissions. By empowering rural communities with compact, CNT-based catalytic systems, it is possible to achieve localized chemical manufacturing, address resource distribution inequities, and promote environmental stewardship through scalable and eco-friendly innovations (Fucà *et al*., 2024).

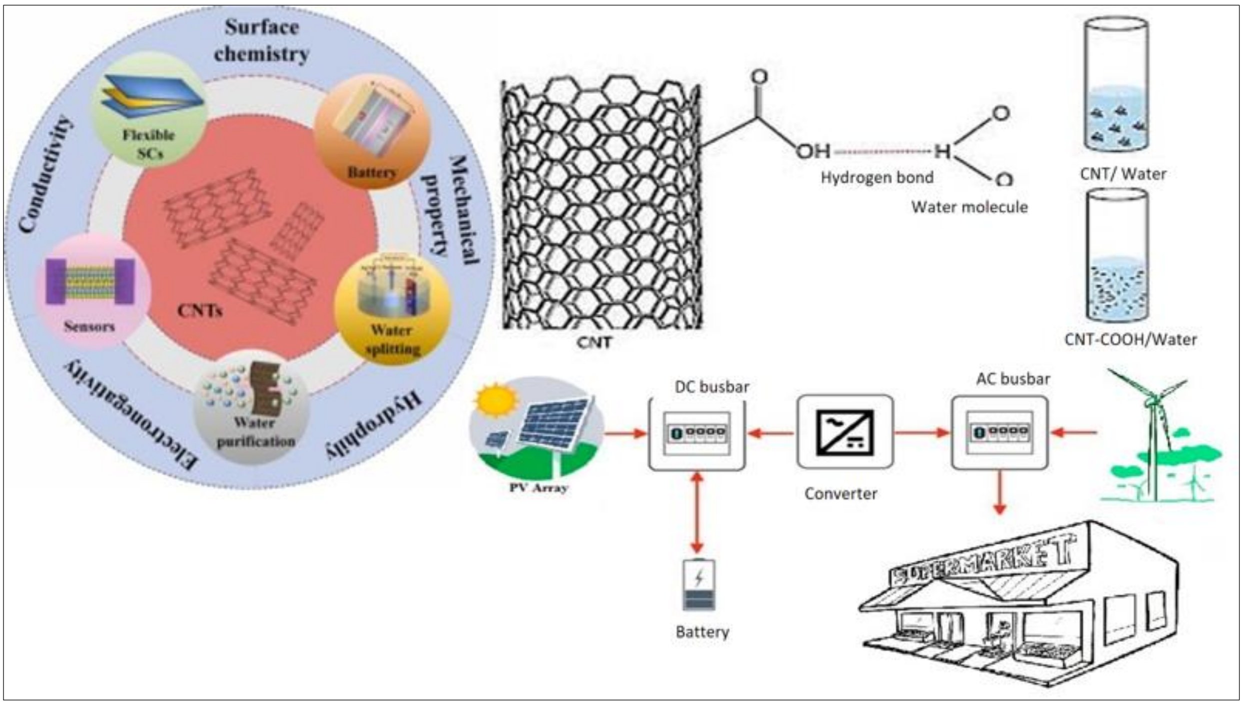


Fig. 2: CNTs in the Era of Decentralized and Off-Grid Solutions, Energy Sovereignty with CNT-enabled Micro-Storage, CNTs in Localized Catalysis for Green Chemistry

CNTs in Immersive and Smart Energy Devices

Because of their exceptional electrical conductivity, mechanical strength, and flexibility, carbon nanotubes (CNTs) are transforming the world of immersive and smart energy devices (Palumbo *et al*., 2022). In the field of wearable technology, carbon nanotubes (CNTs) play a key role in the creation of transparent and stretchy batteries, which allow for seamless integration into wearable technology without sacrificing performance or comfort. These batteries take advantage of CNT-based electrodes' remarkable stretchability and electrochemical stability, which enable them to function effectively even when subjected to constant mechanical deformation. This is crucial for applications in smart textiles, fitness trackers, and health monitors. CNTs are propelling innovation in energy solutions designed for immersive technologies in next-generation augmented and virtual reality (AR/VR) devices. Compact, high-capacity batteries that power AR/VR systems for extended periods without adding bulk are made possible by their lightweight design and superior energy storage characteristics, which improve user mobility and experience (Kim *et al*., 2021). Beyond storage, carbon nanotubes (CNTs) are also being used to generate energy, especially in biomedical implants and e-textiles augmented with CNTs. Through the use of piezoelectric or triboelectric effects, carbon nanotubes (CNTs) in e-textiles serve as effective energy harvesters, transforming mechanical motions into electrical energy that powers integrated sensors and devices in real-time. Similar to this, CNT-based energy systems provide biocompatible ways to power sensors and actuators in biomedical implants, fusing energy efficiency with the capacity to function inside the human body. These developments highlight how CNTs can revolutionize the development of intelligent and immersive energy systems in the future (Moinudeen *et al*., 2017).

CNTs in Interdisciplinary Convergences

The ultimate in multidisciplinary innovation, carbon nanotubes (CNTs) allow for advances in a wide range of disciplines, including synthetic biology, biotechnology, and space exploration (Ajaz *et al*., 2024). CNTs are essential parts of organ-on-chip systems in bio-CNT hybrids, where their remarkable electrical conductivity and biocompatibility enable accurate energy production and real-time monitoring in microfluidic platforms. Researchers can examine cellular behaviors and drug responses with previously unheard-of fidelity thanks to these hybrids, which mimic physiological conditions. High-performance batteries based on carbon nanotubes (CNTs) are revolutionizing energy storage for space travel (Gohardani *et al*., 2014). Their lightweight nature, superior energy density, and robustness against extreme conditions make them ideal for powering spacecraft and planetary rovers while reducing payload costs. Furthermore, by providing scalable solutions for biochemical reactions in living systems, CNT-enabled catalysis is transforming synthetic biology. Their vast surface area and capacity to functionalize with biomolecules improve enzymatic processes, resulting in metabolic engineering, sustainable chemical synthesis, and more effective biofuel generation. The integration of CNTs with biological and synthetic systems not only pushes the boundaries of innovation but also exemplifies the power of interdisciplinary convergence, driving advancements that address critical challenges in energy, healthcare, and exploration (Tawiah *et al*., 2024).

Table 2: Applications of Carbon Nanotubes (CNTs) in Interdisciplinary Convergences

Field	Application	Description	Advantages	Challenges	Future Directions
Bioengineering	Bio-CNT hybrids for organ-on-chip energy production	CNTs are integrated with biological components to mimic tissue behavior while generating energy for organ-on-chip devices.	Enhanced biocompatibility, efficient energy conversion, and scalability for powering microsystems.	Maintaining long-term stability, avoiding cytotoxicity, and ensuring integration with biological systems.	Development of self-healing bio-CNT systems and optimization for medical-grade applications.
Space Exploration	High-performance batteries for extraterrestrial missions	CNTs are utilized in next-generation batteries to improve energy density, reduce weight, and enhance reliability in extreme environments.	Lightweight, radiation resistance, and high power-to-weight ratio essential for long-term space missions.	Cost of production, challenges in battery recycling, and long-term performance under cosmic radiation exposure.	Incorporation with graphene composites to achieve ultra-high energy storage and durability for prolonged space travel.
Synthetic Biology	CNT-enabled catalysis in living systems	CNTs function as catalysts or supports in biochemical reactions, aiding in synthetic biology processes such as enzymatic reactions or biofuel production.	High catalytic efficiency, enhanced reaction rates, and the ability to design tailored reactions.	Potential interference with cellular processes, ensuring non-toxicity, and achieving controlled reactivity in biological environments.	Creation of programmable CNT structures that adapt to cellular needs while boosting bioengineering productivity.
Energy	Integration with renewable energy systems	CNTs are combined with solar cells, fuel cells, or piezoelectric devices to improve energy harvesting and storage.	Increased efficiency, lightweight design, and multifunctionality.	High production costs and need for advanced manufacturing techniques for scalability.	Large-scale deployment in hybrid systems combining solar, thermal, and mechanical energy sources.
Medicine	Drug delivery and biosensors	CNTs serve as nanocarriers for precise drug delivery and as components in biosensors for real-time	Targeted delivery, high surface area for drug loading, and exceptional sensitivity for diagnostic applications.	Ensuring biocompatibility, avoiding immune responses, and achieving controlled degradation.	Advancing CNT-functionalized nanorobots for real-time diagnostics and smart drug delivery systems.

		monitoring of biological markers.			
Environmental Science	CNT-based water purification systems	Utilized in advanced filtration systems to remove pollutants and heavy metals from water.	High filtration efficiency, reusability, and ability to capture a wide range of contaminants.	Controlling the environmental impact of CNT synthesis and disposal, ensuring accessibility in resource-limited settings.	Combining CNTs with eco-friendly materials to create affordable, high-efficiency water treatment systems.
Automotive Industry	Lightweight composites for energy-efficient vehicles	CNTs reinforce polymers in automotive components, reducing weight while maintaining structural integrity.	Improved fuel efficiency, enhanced crash resistance, and reduced environmental impact.	Cost-effective scaling of CNT-reinforced composites and addressing concerns about end-of-life recyclability.	Integration with emerging materials like bio-based polymers to create sustainable automotive solutions.
Agriculture	Smart sensors for precision farming	CNTs are incorporated into sensors for monitoring soil health, moisture levels, and crop conditions in real-time.	Improved agricultural productivity, reduced resource wastage, and adaptability to varying environmental conditions.	Ensuring affordability for widespread adoption and addressing potential environmental concerns of CNT release into ecosystems.	Development of multifunctional CNT-based sensors that can integrate with IoT systems for fully automated smart farming.

Sustainability-Centric Innovations in CNT Production

CNT Growth from Greenhouse Gases

A novel strategy for tackling environmental issues and creating high-performance materials is the synthesis of carbon nanotubes (CNTs) from greenhouse gases (Wang *et al*., 2019). In addition to providing a means of recycling greenhouse gasses, using carbon dioxide (CO_2) or methane directly as fuel for CNT development lessens dependency on traditional fossil-based carbon sources. Using the use of catalysts like transition metals (such as Fe, Ni, or Co) and regulated temperature and pressure, CO_2, a stable and plentiful greenhouse gas, may be reduced to create carbon nanostructures (CNTs) using chemical vapor deposition (CVD) processes. Likewise, methane, a powerful greenhouse gas, is being used more and more to create CNTs, frequently from natural gas flares or industrial emissions. Through this method, dangerous contaminants are converted into useful nanomaterials with exceptional mechanical, electrical, and thermal qualities that may be used in composites, electronics, and energy storage (Mazari *et al*., 2021). In addition to reducing emissions, incorporating such procedures into industrial settings may make circular economy models possible, in which waste gases are converted into new materials. To increase the effectiveness and financial feasibility of these methods and open the door to sustainable CNT manufacture that transforms pollution into performance, advancements in reactor optimization, scalability, and catalyst design are essential (Habib *et al*., 2023).

Waste-to-Nanotube Cycles

Waste-to-Nanotube (W2NT) cycles are a revolutionary approach to waste management and nanotechnology that prioritizes innovation and sustainability (Halagali *et al*., 2025). This technique turns electronic garbage, or "e-waste," a rapidly expanding environmental problem, into materials that are rich in carbon nanotubes (CNTs). Because it contains a range of metals, polymers, and other carbon-rich materials, e-waste can be used as a feedstock for the production of carbon nanotubes (CNTs) using thermal, catalytic, or chemical vapor deposition (CVD) techniques. These techniques efficiently reduce landfill contributions and mitigate environmental impact by using the carbon content of garbage to make CNTs with little energy and resource input (Upadhyayula *et al*., 2012). Furthermore, the W2NT framework's incorporation of closed-loop manufacturing guarantees that CNTs are not only made responsibly but can also be recycled at the end of their useful lives. Deconstructing CNT-based goods, such as electronics, energy storage devices, and advanced composites, enables the nanotubes to be recovered, cleaned, and reincorporated into production cycles. In addition to addressing pressing issues of resource depletion and environmental sustainability, this twin focus on reusing e-waste and facilitating CNT recycling promotes innovation in nanotechnology applications. The W2NT cycle, therefore, demonstrates a circular economic paradigm where waste becomes a valuable resource, contributing to a greener and more technologically advanced future (Ghisellini *et al*., 2016).

Disrupting the Status Quo: Speculative Futures with CNTs

The incorporation of carbon nanotubes (CNTs) into cutting-edge applications has the potential to upend established paradigms in a number of domains and portend imaginative futures where sustainability and innovation coexist (Kumar *et al*., 2024). CNT-enabled "energy-on-demand" technologies provide one of the most revolutionary possibilities because of their remarkable electrical conductivity and thermal stability, which enable extremely effective energy storage and quick delivery systems. These innovations have the potential to revolutionize portable power solutions, including supercapacitors and next-generation batteries, by facilitating rapid energy transfer and facilitating seamless integration with smart grid infrastructures, wearable technology, and electric cars. Simultaneously, a hitherto unheard-of synergy between urbanization and sustainability is introduced by the development of CNT-based catalytic smart cities (Luo *et al*., 2024). In this case, CNTs power adaptive energy systems and serve as sophisticated catalysts for environmental remediation, turning urban pollutants into recyclable resources. In order to create sustainable urban ecosystems, these smart cities—powered by CNT-enabled infrastructure may have self-cleaning air systems, renewable energy grids, and effective water purification systems. Looking further forward, quantum CNTs for fusion-energy-related catalysis provide a theoretical leap into new areas of energy creation. By harnessing the quantum mechanical features of CNTs, these structures might permit the severe conditions necessary for nuclear fusion, offering a practically endless, clean energy source. Together, these achievements establish CNTs as a cornerstone in the continuing reinvention of technological and environmental paradigms, bridging the gap between speculative research and operational innovation (Tawiah *et al*., 2024).

Policy, Ethics, and the CNT Revolution

Although the CNT revolution offers enormous potential for developing sectors, its broad use requires a delicate balancing act between ecology, ethics, and politics (Tawiah *et al*., 2024). The ethical sourcing of the materials needed to produce CNTs, especially rare earth elements and other essential resources, lies at the heart of this problem. To stop ecological degradation and exploitation, supply chains must be transparent, eco-friendly, and considerate of workers' rights. At the same time, regulatory frameworks that address the special characteristics of CNTs and concentrate on their safe use in a range of applications must be created. Thorough testing and standardization of handling protocols are necessary to mitigate the possible health and environmental hazards linked to the discharge of carbon nanotube particles into the environment. To guarantee the long-term viability of CNT technology, policymakers must create thorough regulations that cover lifespan analyses and recycling plans (Kim *et al*., 2024). In order to stop socioeconomic gaps from growing, fair access to CNT-driven technologies is also essential. Fostering public-private collaborations, encouraging open innovation platforms, and offering financial aid or incentives for the widespread use of technology are all examples of effective strategies. By democratizing access to CNT applications in manufacturing, healthcare, and energy, these policies may ensure that society as a whole benefits from their transformational potential while responsibly tackling global issues. When combined, these strategies will allow for a responsible and moral revolution in CNT (Vallero *et al*., 2007).

CONCLUSION

Because of their special physical, chemical, and electrical characteristics, carbon nanotubes (CNTs) have become a game-changing material in the domains of batteries and catalysis. CNTs have shown remarkable promise in battery technology for increasing charge-discharge rates, prolonging battery lifespans, and boosting energy storage efficiency, especially in applications like lithium-ion, sodium-ion, and newly developed solid-state batteries. They solve important issues, including capacity deterioration and temperature stability as conductive additives or active components. Similar to this, CNTs are perfect for promoting reactions in fields like fuel cells, hydrogen generation, and CO_2 reduction due to their large surface areas, superior electron transport capabilities, and customizable chemical functions. Catalytic effectiveness is further increased by their capacity to host metal nanoparticles with improved stability. With their smooth integration into cutting-edge systems for the production, storage, and use of renewable energy, carbon nanotubes (CNTs) are positioned to play a significant role in enabling sustainable energy and chemical solutions in the future. They have the ability to propel the shift to a circular economy because of their role in enabling green technologies like artificial photosynthesis and zero-carbon fuels. Innovations in CNT synthesis, functionalization, and scalability will open up new avenues as research advances, reaffirming their status as a key component of energy-efficient and sustainable developments for a cleaner future.

REFERENCES

- Afroz, A. S., Romano, D., Inglese, F., & Stefanini, C. (2021). Towards bio-hybrid energy harvesting in the real world: pushing the boundaries of technologies and strategies using bio-electrochemical and bio-mechanical processes. *Applied Sciences*, *11*(5), 2220.

- Agbelusi, J., Arowosegbe, O. B., Alomaja, O. A., Odunfa, O. A., & Ballali, C. (2024). Strategies for minimizing carbon footprint in the agricultural supply chain: leveraging sustainable practices and emerging technologies. *World Journal of Advanced Research and Reviews*, *23*(3), 2625-2646.
- Aggarwal, S., & Ikram, S. (2023). A comprehensive review on bio-mimicked multimolecular frameworks and supramolecules as scaffolds for enzyme immobilization. *Biotechnology and Bioengineering*, *120*(2), 352-398.
- Ajaz, M., Rasool, W., & Mahmood, A. (2024). Comprehensive Review of Nanotechnology: Innovations and Multidisciplinary Applications: Comprehensive Review of Nanotechnology. *Futuristic Biotechnology*, 12-18.
- Basu, M. (2024). Tech-Driven Horizons: Pioneering Sustainable Tourism for Environmental Resilience and SDGs Triumph. In *The Need for Sustainable Tourism in an Era of Global Climate Change: Pathway to a Greener Future* (pp. 215-247). Emerald Publishing Limited.
- Betz, U. A., Arora, L., Assal, R. A., Azevedo, H., Baldwin, J., Becker, M. S., ... & Zhao, G. (2023). Game changers in science and technology and beyond. *Technological Forecasting and Social Change*, *193*, 122588.
- Chadha, U., Selvaraj, S. K., Ashokan, H., Hariharan, S. P., Mathew Paul, V., Venkatarangan, V., & Paramasivam, V. (2022). Complex nanomaterials in catalysis for chemically significant applications: from synthesis and hydrocarbon processing to renewable energy applications. *Advances in Materials Science and Engineering*, *2022*(1), 1552334.
- Chakrabartty, I., Hakeem, K. R., Mohanta, Y. K., & Varma, R. S. (2022). Greener nanomaterials and their diverse applications in the energy sector. *Clean Technologies and Environmental Policy*, *24*(10), 3237-3252.
- Chen, G., & Tang, D. M. (2024). Machine Learning as a “Catalyst” for Advancements in Carbon Nanotube Research. *Nanomaterials*, *14*(21), 1688.
- Chen, J. (2019). Graphene quantum dots and their applications in bioimaging and catalysis.
- Chen, L., Liu, Z., Guo, Z., & Huang, X. J. (2020). Regulation of intrinsic physicochemical properties of metal oxide nanomaterials for energy conversion and environmental detection applications. *Journal of Materials Chemistry A*, *8*(34), 17326-17359.
- Chen, L., Xu, S., & Li, J. (2011). Recent advances in molecular imprinting technology: current status, challenges and highlighted applications. *Chemical Society Reviews*, *40*(5), 2922-2942.
- Chen, Y., Wang, L., Yao, Z., Hao, L., Tan, X., Masa, J., ... & Sun, Z. (2022). Tuning the coordination structure of single atoms and their interaction with the support for carbon dioxide electroreduction. *Acta Phys Chim Sin*, *38*(11), 2206020.
- Dariyal, P., Sehrawat, M., Dhakate, S. R., & Singh, B. P. (2023). 6 Carbon Graphene Nanotubes for and Conducting Wires. *Emerging Applications of Carbon Nanotubes and Graphene*, 105.
- Fucà, R., Cubico, S., Leitão, J., Favretto, G., & Ardolino, P. (2024). Post-COVID-19 Advancing Targeted Drug Delivery (TDD): Literature Insights and Market Dynamics. *Emerging Social Issues on Targeted Drug Delivery*, 255.
- Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11-32.
- Gohardani, O., Elola, M. C., & Elizetxea, C. (2014). Potential and prospective implementation of carbon nanotubes on next-generation aircraft and space vehicles: A review of current and expected applications in aerospace sciences. *Progress in Aerospace Sciences*, *70*, 42-68.
- Gupta, S., & Ray, B. C. (2022). Self-Healing and Shape Memory Effects of Carbon Nanotube–Based Polymer Composites. *Handbook of Carbon Nanotubes*, 1113-1146.
- Habib, U., Ahmad, F., Awais, M., Naz, N., Aslam, M., Urooj, M., ... & Shabbir, M. J. (2023). Sustainable Catalysis: Navigating Challenges and Embracing Opportunities for a Greener Future. *Journal of Chemistry and Environment*, *2*(2), 14-53.
- Halagali, P., Nayak, D., Rathnanand, M., Tippavajhala, V. K., Sharma, H., & Biswas, D. (2025). Synergizing sustainable green nanotechnology and AI/ML for advanced nanocarriers: A paradigm shift in the treatment of neurodegenerative diseases. In *The Neurodegeneration Revolution* (pp. 373-397). Academic Press.
- Hashem, I. A. T., Usmani, R. S. A., Almutairi, M. S., Ibrahim, A. O., Zakari, A., Alotaibi, F., ... & Chiroma, H. (2023). Urban computing for sustainable smart cities: Recent advances, taxonomy, and open research challenges. *Sustainability*, *15*(5), 3916.
- Islam, M. A., Hasan, M., Rahman, M., Mobarak, M. H., Mimona, M. A., & Hossain, N. (2024). Advances and significances of carbon nanotube applications: A comprehensive review. *European Polymer Journal*, 113443.
- Isola, L. A., Chen, T. C., Elveny, M., Alkaim, A. F., Thangavelu, L., & Kianfar, E. (2022). Application of micro and porous materials as nano-reactors. *Reviews in Inorganic Chemistry*, *42*(2), 121-136.
- Jha, R., Singh, A., Sharma, P. K., & Fuloria, N. K. (2020). Smart carbon nanotubes for drug delivery system: A comprehensive study. *Journal of Drug Delivery Science and Technology*, *58*, 101811.

- Karkera, G., Reddy, M. A., & Fichtner, M. (2021). Recent developments and future perspectives of anionic batteries. *Journal of Power Sources*, *481*, 228877.
- Khlobystov, A. N. (2011). Carbon nanotubes: from nano test tube to nano-reactor. *ACS nano*, *5*(12), 9306-9312.
- Kim, J. J., Wang, Y., Wang, H., Lee, S., Yokota, T., & Someya, T. (2021). Skin electronics: next-generation device platform for virtual and augmented reality. *Advanced Functional Materials*, *31*(39), 2009602.
- Kim, M., Goerzen, D., Jena, P. V., Zeng, E., Pasquali, M., Meidl, R. A., & Heller, D. A. (2024). Human and environmental safety of carbon nanotubes across their life cycle. *Nature Reviews Materials*, *9*(1), 63-81.
- Kothandam, G., Singh, G., Guan, X., Lee, J. M., Ramadass, K., Joseph, S., ... & Vinu, A. (2023). Recent Advances in Carbon-Based Electrodes for Energy Storage and Conversion. *Advanced Science*, *10*(18), 2301045.
- Kumar, S., Sharma, I., & Kumar, A. (2024). Disruptive Innovations using Tech-Business Analytics. *Tuijin Jishu/Journal of Propulsion Technology*, *45*(1), 2376-2396.
- Li, F., Yue, S., Zhao, Z., Liu, K., Wang, P., & Zhan, S. (2024). Application of molecularly imprinted polymers in the water environmental field: A review on the detection and efficient removal of emerging contaminants. *Materials Today Sustainability*, 100904.
- Li, G. (2021). Regulating mass transport behavior for high-performance lithium metal batteries and fast-charging lithium-ion batteries. *Advanced Energy Materials*, *11*(7), 2002891.
- Luo, K., Peng, H., Zhang, B., Chen, L., Zhang, P., Peng, Z., & Fu, X. (2024). Advances in carbon nanotube-based gas sensors: Exploring the path to the future. *Coordination Chemistry Reviews*, *518*, 216049.
- Mazari, S. A., Ali, E., Abro, R., Khan, F. S. A., Ahmed, I., Ahmed, M., ... & Shah, A. (2021). Nanomaterials: Applications, waste-handling, environmental toxicities, and future challenges–A review. *Journal of Environmental Chemical Engineering*, *9*(2), 105028.
- Mishra, R. K., & Verma, K. (2024). Defect engineering in nanomaterials: Impact, challenges, and applications. *Smart Materials in Manufacturing*, *2*, 100052.
- Moinudeen, G. K., Ahmad, F., Kumar, D., Al-Douri, Y., & Ahmad, S. (2017). IoT applications in the future are foreseen guided by engineered nanomaterials and printed intelligence technologies, according to a technology review. *International Journal of Internet of Things*, *6*(3), 106-148.
- Mondal, U., & Yadav, G. D. (2021). Methanol economy and net zero emissions: a critical analysis of catalytic processes, reactors and technologies. *Green Chemistry*, *23*(21), 8361-8405.
- Nawaz, M. A., Blay-Roger, R., Saif, M., Meng, F., Bobadilla, L. F., Reina, T. R., & Odriozola, J. A. (2024). Redefining the Symphony of Light Aromatic Synthesis Beyond Fossil Fuels: A Journey Navigating through a Fe-Based/HZSM-5 Tandem Route for Syngas Conversion. *ACS catalysis*, *14*(20), 15150-15196.
- Nepal, D., Kang, S., Adstedt, K. M., Kanhaiya, K., Bockstaller, M. R., Brinson, L. C., ... & Heinz, H. (2023). Hierarchically structured bioinspired nanocomposites. *Nature Materials*, *22*(1), 18-35.
- Palumbo, A., Li, Z., & Yang, E. H. (2022). Trends on carbon nanotube-based flexible and wearable sensors via electrochemical and mechanical stimuli: a review. *IEEE Sensors Journal*, *22*(21), 20102-20125.
- Rao, R., Pint, C. L., Islam, A. E., Weatherup, R. S., Hofmann, S., Meshot, E. R., ... & Hart, A. J. (2018). Carbon nanotubes and related nanomaterials: critical advances and challenges for synthesis toward mainstream commercial applications. *ACS nano*, *12*(12), 11756-11784.
- Rathinavel, S., Priyadharshini, K., & Panda, D. (2021). A review on carbon nanotube: An overview of the synthesis, properties, functionalization, characterization, and application. *Materials Science and Engineering: B*, *268*, 115095.
- Sabet, M. (2024). Advanced Functionalization Strategies for Carbon Nanotube Polymer Composites: Achieving Superior Dispersion and Compatibility. *Polymer-Plastics Technology and Materials*, 1-30.
- Sagar, S. (2023). Innovation and Sustainability in Business: Navigating the Future Landscape. *IOSR Journal of Business and Management (IOSR-JBM)*, *25*(12), 51-60.
- Said, Z., Sohail, M. A., Pandey, A. K., Sharma, P., Waqas, A., Chen, W. H., ... & Nguyen, X. P. (2023). Nanotechnology-integrated phase change material and nanofluids for solar applications as a potential approach for clean energy strategies: Progress, challenges, and opportunities. *Journal of Cleaner Production*, *416*, 137736.
- Sharfstein, S. T. (2022). Bio-hybrid electronic and photonic devices. *Experimental Biology and Medicine*, *247*(23), 2128-2141.
- Shukla, V., & Siddiqui, K. A. (2024). Photocatalytic Plastic Degradation: Challenges and Sustainable Pathways. In *Plastic Degradation and Conversion by Photocatalysis (Volume 1): A Sustainable Approach* (pp. 223-245). American Chemical Society.
- Singh, B., Sharma, V., Gaikwad, R. P., Fornasiero, P., Zbořil, R., & Gawande, M. B. (2021). Single-atom catalysts: a sustainable pathway for the advanced catalytic applications. *Small*, *17*(16), 2006473.

- Stachowska, J. (2021). *Nanocomposites based on fluorescent carbogenic nanoparticles for biomedical applications* (Doctoral dissertation, University of Central Lancashire).
- Tawiah, B., Ofori, E. A., & George, S. C. (2024). Nanotechnology in societal development. In *Nanotechnology in Societal Development* (pp. 1-64). Singapore: Springer Nature Singapore.
- Upadhyayula, V. K., & Gadhamshetty, V. (2010). Appreciating the role of carbon nanotube composites in preventing biofouling and promoting biofilms on material surfaces in environmental engineering: a review. *Biotechnology advances*, *28*(6), 802-816.
- Upadhyayula, V. K., Meyer, D. E., Curran, M. A., & Gonzalez, M. A. (2012). Life cycle assessment as a tool to enhance the environmental performance of carbon nanotube products: a review. *Journal of Cleaner Production*, *26*, 37-47.
- Vallero, D. A. (2007). Beyond responsible conduct in research: new pedagogies to address macroethics of nanobiotechnologies. *Journal of long-term effects of medical implants*, *17*(1).
- Verma, S., & Yadav, A. (2023). Emerging single-atom catalysts and nanomaterials for photoelectrochemical reduction of carbon dioxide to value-added products: a review of the current state-of-the-art and future perspectives. *Energy & Fuels*, *37*(8), 5712-5742.
- Wang, D., Saleh, N. B., Sun, W., Park, C. M., Shen, C., Aich, N., ... & Su, C. (2019). Next-generation multifunctional carbon–metal nanohybrids for energy and environmental applications. *Environmental science & technology*, *53*(13), 7265-7287.
- Weerarathna, I. N., Kumar, P., Luharia, A., & Mishra, G. (2024). Engineering with Biomedical Sciences Changing the Horizon of Healthcare Review. *Bioengineered*, *15*(1), 2401269.
- Xu, Z., Liu, Y., Ren, F., Yang, F., & Ma, D. (2016). Development of functional nanostructures and their applications in catalysis and solar cells. *Coordination Chemistry Reviews*, *320*, 153-180.
- Yan, Y., Miao, J., Yang, Z., Xiao, F. X., Yang, H. B., Liu, B., & Yang, Y. (2015). Carbon nanotube catalysts: recent advances in synthesis, characterization and applications. *Chemical Society Reviews*, *44*(10), 3295-3346.
- Yang, Z., Ren, J., Zhang, Z., Chen, X., Guan, G., Qiu, L. & Peng, H. (2015). Recent advancement of nanostructured carbon for energy applications. *Chemical Reviews*, *115*(11), 5159-5223.
- Yazdi, A. A., D'Angelo, L., Omer, N., Windiasti, G., Lu, X., & Xu, J. (2016). Carbon nanotube modification of microbial fuel cell electrodes. *Biosensors and Bioelectronics*, *85*, 536-552.
- Zhang, X. Q., Zhao, C. Z., Huang, J. Q., & Zhang, Q. (2018). Recent advances in energy chemical engineering of next-generation lithium batteries. *Engineering*, *4*(6), 831-847.