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Recent trends and perspectives of carbon-based nanocomposites for multifunctional applications

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A B S T R A C T

Carbon-based nanocomposites are a new type of multifunctional materials that combine mechanical, electrical, and thermal properties in a unique and useful manner and have allowed the use of these materials to change technology. The latest trends indicate that there are many significant advancements occurring in the development of carbon nanotube-enhanced polymer nanocomposite materials. Carbon-based nano composites offer superior performance compared to other types of conventional materials. There is an ongoing direction toward developing innovative design and manufacturing techniques for carbon-based nanocomposites, through sustained investment into new product development, research, and development of next generation multi-functional carbon-based nanocomposite products for cutting-edge application technologies.

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1. Introduction

Nanocomposite material comprises many phases, with at least one, two, or three dimensions in the nanoscale range. Minimizing material dimensions to the nanoscale creates phase interfaces that are essential for the evolution of material properties [1, 2]. The ratio of surface area to volume of reinforced material utilized in nanocomposite preparation is directly related to the comprehension of the structure-property relationship [3-5]. Nanocomposites represent a category of materials currently utilized across various sectors, including nanoelectronics and energy storage, owing to their remarkable electrical, mechanical, and chemical capabilities. These materials have fundamentally transformed the realm of "functional materials" and can thus be regarded as the materials of the 21st century, with ongoing study of novel paths occurring often [2, 6, 7].

Among various nanocomposites, carbon-based nanocomposites (CNCs) have garnered significant attention over

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the past two decades owing to their structure-dependent electrical characteristics, low density, and extensive specific surface area [8, 9].

CNCs are made from multiple carbonaceous materials, i.e. graphite, nanotubes, C60, and contain many different types of matrix materials that reinforce many different types of materials such as metal oxides, sulfides, nitrides [10]. the extensive charge transfer capacities of adsorbing agents allow CNC's based upon Carbon Nanotubes (CNT's) to offer significant opportunities for utilization in many diverse applications including electrochemical supercapacitors, gas sensors, biological sensors, electromagnetic absorbers and photovoltaic cells, as well as in the biomedical industry [11, 12]. Consequently, they are regarded as promising materials for enhancing the creation of extremely sensitive, selective, and efficient drug delivery systems, drug release mechanisms, and excellent tissue regeneration capabilities. Current research aims to develop ultra-sensitive biosensors utilizing the exceptional conductivity and quenching properties of them for drug delivery systems, as well as to create practical nanomaterial electron-conducting substrates with outstanding biocompatibility for tissue regeneration [13, 14]. Moreover, Carbon-based materials were found to be very effective in the removal of nitric oxide, hydrogen sulfide, heavy metals, dyes, pharmaceutical products and other contaminants from the environment [15]. Fig. 1 illustrates a map of recent research about carbon-based nanocomposites for several applications (data extracted from Scopus from 2020 to 2024).

The purpose of this review investigates carbon-based nanocomposites, their integration with other nanomaterials, and their applications in energy storage, sensing, and biological fields, along with a selective summary of recent studies. Initially, several carbon nanomaterials, including CNTs, graphene, carbon dots (CDs), and carbon-based nanocomposites including other recently identified nanomaterials, are examined. Subsequently, according to the specific themes that are presently the focus of extensive investigation.

2. Fundamentals of carbon-based nanomaterials

Carbon-based nanomaterials are highly versatile and have unique atomic structures, properties, and conductivities that make them attractive for use in multiple industries.

They can be used in the following industries: energy generation and storage, catalysis, electronics, industrial, and biomedical applications. The most commonly used carbon-based nanomaterials are carbon nanotubes (CNTs), graphene, carbon nanofibers (CNFs), carbon nanodots (CNDs), nanodiamonds, and hybrid hierarchical nanostructures. The most common carbon nanostructures are shown in Fig. 2.

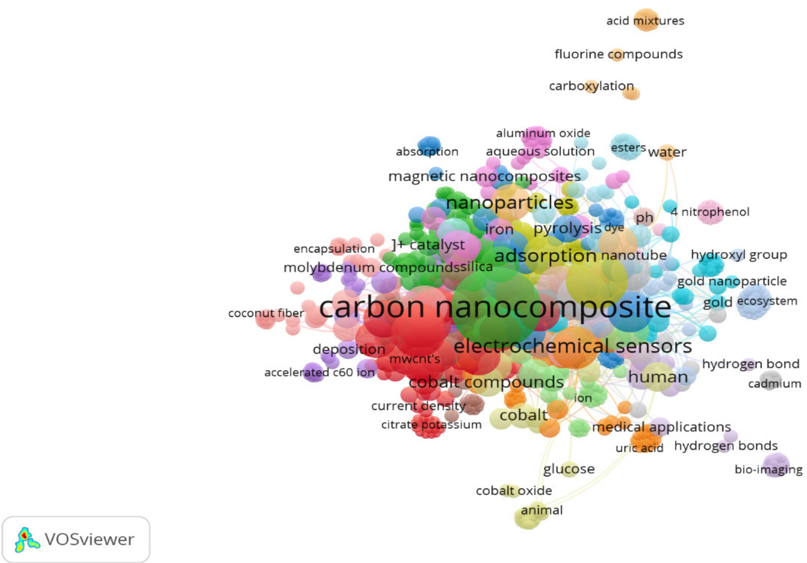

Fig. 1. Carbon-based nanocomposites for multifunctional applications.

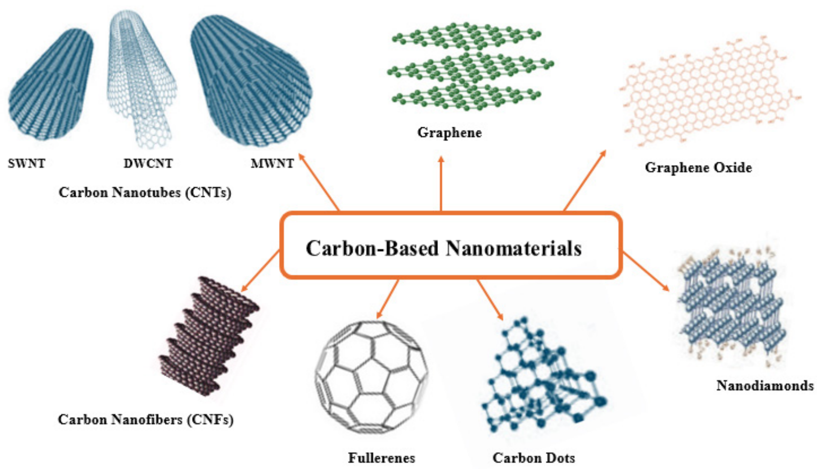

Fig. 2. Carbon-based nanomaterials.

2.1. Carbon nanotubes (CNTs)

Carbon nanotubes are distinctive tubular formations with a nanometer diameter and a substantial length-to-diameter ratio. Nanotubes can have anywhere from one to hundreds of concentric carbon shells, with each shell being about 0.34 nm apart [16].

Graphene sheets are twisted into cylindrical shapes to make CNTs. The smallest CNTs are only one nanometer in diameter [17]. Carbon nanotube (CNT) types are generally classified into three main types, single-wall, double-wall, and multi-wall; they can differ in respect to length, diameter, density, and mechanical properties. Therefore, this affects them for use in specific applications [18].

Various methods to synthesize CNTs including laser ablation, carbon high-pressure disproportionation, chemical vapour deposition (CVD) [55]. The CVD process is the dominant technique, particularly because of the advantages offered through high production potential relative to other CNTS' synthesis techniques. The carbon nanotube produced by this approach exhibits a significant length and improved morphological properties [19].

As nanotubes have evolved through advancements in manufacturing and characterization methods, the emerging applications of nanotubes have. Subsequently, theories surrounding the higher yield strength and elastic modulus to be obtained from nanotubes led researchers to speculate about utilizing nanotubes in improved composite materials with improved mechanical properties [20, 21]. Nanotubes are well-suited for use in electron field emission due to their extremely small size, strength, and excellent conductivity and stability as well as their capacity to be used in flat panel displays [22].

Multiwall nanotubes have been employed to electrocatalysis the oxygen reduction reaction, which is crucial for fuel cells [23]. Electrochemically Li-intercalated SWNT materials exhibited significant irreversible capacity and voltage hysteresis, presenting an advantage for their application as battery electrodes [24]. CNTs have high surface areas and drug loading capacity, making them ideal for drug delivery. Their nanometric scale, functionalization options, and drug delivery capabilities are attracting attention. Current CNTs have defects that prevent their usage in pharmaceuticals, which must be overcome. The main reason is that they are not biodegradable and may be poisonous over time [25].

2.2. Graphene and graphene oxide

Graphene is the material that is constructed from carbon atoms that are chemically bound together by a process known as sp2 hybridization. These atoms are arranged in a pattern of hexagons, which gives the material a honeycomb-like shape [26]. As a result of its conventional two-dimensional structure, it exhibits a variety of remarkable and distinctive properties, including the fact that it is the most conductive, lightest, strongest, and most transparent substance of its type [27].

On the other hand, graphene oxide (GO) is a substance that garners significant interest among the scientific community owing to its distinctive physical and chemical properties. The characteristics can be adjusted by altering the oxidation level, the dimensions and morphology of the flakes, and the chemical functionalization, rendering it a versatile material with significant promise for many applications [28].

Graphene-based material has good electrical, thermal, and mechanical. properties, making it a promising contender for use in energy storage, biosensors, biomedical engineering, hydrogen storage, displays, and solar cells [29-31].

Schematic representation of the primary graphene production methods is shown in Fig. 3, these methods can be categorized as follows: (a) cleavage that is micromechanical in nature (b) the process of anodic bonding (c) the process of using light to remove unwanted material from the skin (d) the process of exfoliation when in the liquid phase(e) SiC is a material that can grow. The gold and gray spheres in the diagram are used to symbolize silicon (Si) and carbon (C) atoms. When the temperature (T) is increased, the silicon atoms (Si) evaporate, as indicated by the arrows. This process results in the formation of graphene sheets on a surface that is rich in carbon. (f) The process of segregating or precipitating from a metal substrate that contains carbon (g) the process of depositing chemicals through the use of vapor (h) the technique of epitaxy using a molecular beam (i) The production of chemicals through synthesis, with benzene being utilized as the building block [32].

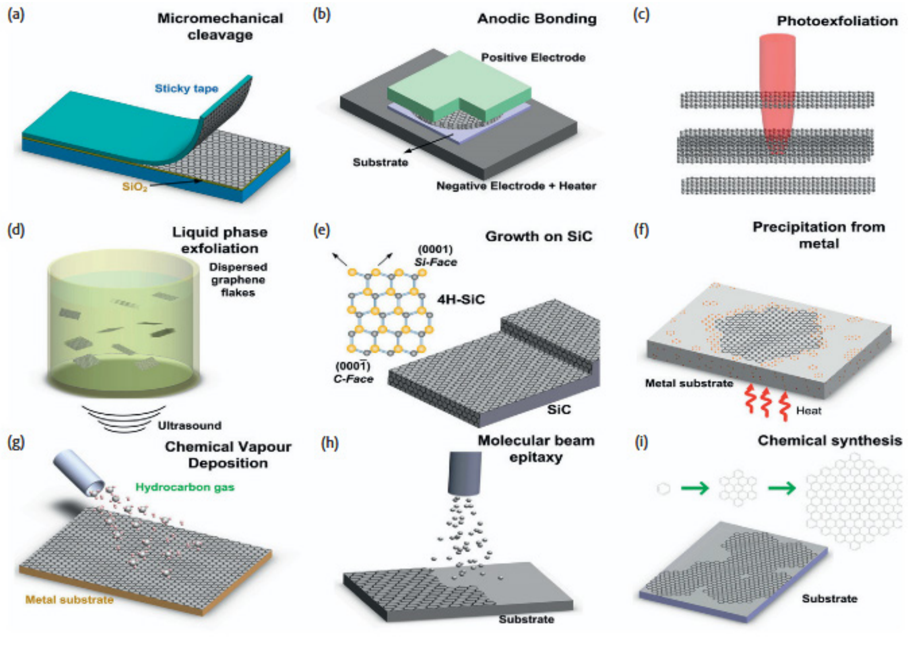

Fig. 3. The main techniques for production of graphene [32].

2.3. Carbon nanofibers (CNFs)

Carbon nanofibers (CNFs) are defined as vapor-grown nanoscale fibrils with diameters between approximately 50 and 200 nm [33]. CNFs relate to the covalent carbon nanomaterial (CNM) family and exhibit conductivity and stability akin to CNTs. The arrangement of graphene sheets in different configurations differentiates CNFs from CNTs, leading to a greater number of edge sites on the exterior surfaces of CNFs compared to CNTs. This may facilitate the electron transport of an electroactive analyte [34].

CNFs can be generated through vapor phase growth via chemical vapor deposition or by carbonizing pre-synthesized polymer nanofibers. Both procedures provide a simpler synthesis of CNFs in contrast to CNTs. The synthesis procedures considerably influence their structure and properties. Carbon nanofibers, due to their graphitic structure, provide distinctive features like exceptional corrosion resistance, mechanical strength , and thermal and electrical conductivities [35].

2.4. Carbon dots and nanodiamonds

Carbon dots (CDs) denote a category of carbon-based nanoparticles categorized into distinct subgroups according to their crystallinity and shape. CDs provide adjustable physical, chemical, and optical characteristics that can be regulated by straightforward one-pot synthesis methods. Moreover, their non-toxicity, biocompatibility, chemical and physical responsiveness, resistance to photo- and chemical-bleaching, and affordability facilitate a variety of applications [36]. Common CDs are classified as a type of 0D carbon-dominated nanomaterial, typically measuring less than 20 nm, comprising a sp^2/sp^3 carbon framework and many functional groups/polymer chains [37].

2.5. Fullerenes

The exploration of carbon nanostructures commenced with the identification of fullerenes. Fullerenes are closed hollow structures composed of sp2-hybridized carbon atoms organized into 12 pentagons and a variable number of hexagons, contingent upon the overall carbon atom count. Numerous other fullerenes have been identified, such as C20, C70, and larger variants; nonetheless, C60 remains the most extensively researched to date [38]. C60, exhibits icosahedral symmetry (Ih) and consists of 20 hexagons derived from a graphene sheet, folded to form 12 pentagons, thereby adhering to Euler's formula, with all carbon atoms being equivalent and exhibiting near-sp2 hybridization. At normal temperature, C60 crystallizes in a face-centered cubic structure, with a unit cell parameter of 14.2 Å [39, 40].

3. Design and fabrication of carbon-based nanocomposites

New carbon-based nanocomposite technology has been developed for use in polymers, metals, and ceramic matrices. The successful application of nanocomposite technology is related to both the strategic design of the architecture of the nanocomposite and the use of nanomaterials within the nanocomposite [41].

Research on the fabrication techniques used to produce polymer-matrix composites will depend on the type of polymer used in their manufacture; however, it can generally be recognized that the methods for producing such composites include solution mixing, in situ polymerization and the use of covalently bonded grafts; metal-matrix composites can also employ carbon-based materials to increase both the electrical conductivity and tensile strength of their respective matrices; and ceramic-based composite matrices can utilize additional carbon based materials to modify the overall structural properties of the composite matrices. The principal benefit of these synergistic interactions between carbon-based nanomaterials and the various types of matrix materials is that they allow for the production of advanced functional composite materials for multifunctional applications [42, 43].

3.1. Polymer-matrix carbon nanocomposites

In recent decades, the demand for advanced materials has surged significantly. In several industries, materials with superior mechanical, electrical, and thermal qualities are strongly advocated. The utilization of tidy materials was significantly limited due to their often-inadequate amalgamation of intrinsic features. Conversely, composite materials possess the capability to fulfill emerging requirements. Polymer-matrix composites reinforced with CNTs demonstrate exceptional physical properties [44]. Recent research has focused intensely on the synthesis, characterization, and use of polymer–carbon nanotube composites, motivated by an increasing acknowledgment of the distinctive mechanical, thermal, electrical, and other material properties of carbon nanotubes [45, 46]. Substantial efforts have been undertaken in the synthesis of these nanocomposites by incorporating either SWNT or MWNT carbon nanotubes into diverse polymer matrices. For instance, carbon nanotubes have been integrated into matrices of conjugated polymers, such as poly(phenylenevinylene) (PPV) and its derivatives, to create composites with notable optoelectronic properties. Carbon nanotubes have been utilized as fillers in epoxy resin to leverage their exceptional mechanical properties. Solution-phase processing is a widely employed technique for dispersing carbon nanotubes and subsequently fabricating nanocomposites. Nonetheless, carbon nanotubes are insoluble and aggregated, posing a considerable obstacle for their uniform dispersion in polymer matrices. Successful methods for dispersion encompass the sonication of carbon nanotubes with polymers, including PPV derivatives, poly(vinylpyrrolidone), and starch, as well as the in-situ polymerization of monomers alongside carbon nanotubes [47].

Numerous potential applications of polymer-carbon nanotube composite materials have been suggested and investigated (Fig. 4) [48].

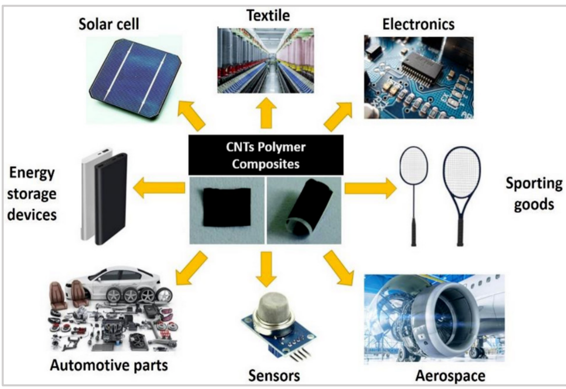

Fig. 4. Application of polymer-matrix carbon nanocomposites [49].

3.2. Metal-matrix carbon nanocomposites

The goal of developing lightweight metal matrix composites (MMCs) with superior performance for structural applications has been undertaken among composite materials. MMCs are recognized for their capacity to preserve the advantageous characteristics of metals while maintaining the strength and stiffness constraints inherent in monolithic metals [50].

Reinforcement materials are essential for MMCs. Traditionally, they consisted of carbon ,ceramic, or other high-stiffness particles, whiskers, small fibers, or continuous fibers [51, 52]. To achieve lightweight, high-strength MMCs, it is essential to utilize high-strength and lightweight reinforcement elements [53]. Carbon compounds, including graphite, carbon fibers, CNTs, and graphene, are particularly notable. Graphene is regarded as the most robust material globally. It possesses remarkable attributes: outstanding electrical characteristics, high thermal conductivity, elevated Young's modulus, and significant tensile strength [54, 55]. Since its discovery by Geim et al [56] , numerous studies have been conducted on the application of graphene as a reinforcement in polymers and metal matrices. A variety of graphene-based polymer composites have been documented. In addition, one-dimensional carbon nanotubes and two-dimensional graphene nanosheets with unique thermal, mechanical, and electrical capabilities. Recent nanotechnology breakthroughs allow the fabrication of sophisticated metal matrix nanocomposites for functional devices and structural engineering [57]. Moreover, Carbon fibers (CFs) reinforced MMCs have been investigated for heat sink applications to balance machinability and thermo-mechanical characteristics. Only 30% carbon fiber reinforcing reduced aluminum and copper CTE, according to Lalet et al.[58]. Additionally, S. E. Shin et al. [50] present a novel model for predicting the strength and stiffness of MMNCs, grounded in a quantitative analysis of efficiency metrics that significantly highlights the interface characteristics. To validate the model, they choose MWCNT and FLG as reinforcements and titanium (Ti) and aluminum (Al) as the matrix to enhance bonding strength in the MMNCs.

3.3. Ceramic-matrix carbon nanocomposites

Nanotubes appear to be promising materials for reinforcement in composites, especially in ceramic-matrix composites. Many researchers have sought to utilize CNT to improve the mechanical properties of composites. Ceramic materials enhanced with CNT appear to be effective toughening agents, resulting in reduced brittleness and composites exhibiting much superior fracture toughness compared to the original ceramics [59-61]. Numerous techniques are employed to synthesize CNTs, including arc discharge with or without metal, laser vaporization of a metal-graphite composite target, carbon monoxide disproportionation, and catalytic breakdown of hydrocarbons on tiny metallic catalysts (Cu, Ni, Co, Fe)[62]. Nonetheless, spark plasma sintering (SPS), as an innovative and effective consolidation method, is utilized for the complete densification of high-temperature ceramic systems. In these binary nanocomposites, CNTs are incorporated into ceramic matrices to significantly enhance their suboptimal characteristics, and SPS is utilized to create totally dense compacts [63]. Purification is typically necessary due to the production of several carbon forms in addition to CNTs. Furthermore ,it is crucial to ensure a uniform dispersion of CNTs within the ceramic powder in order to create a CNTs–ceramic composite from the prepared CNTs [64].

4. Recent trends of carbon nanocomposites in energy applications

Recent trends in carbon nanocomposites for energy applications emphasize the advancement of graphene-based materials, especially three-dimensional graphene structures and their integration with carbon nanotubes [65]. Through the application of these types of nanocomposite structures, there is increased available charge and enhanced cycling stability for all of the applications of energy which include electromagnetic equipment: fuel cells, lithium-ion batteries, supercapacitors and dye-sensitized solar cells. Yet the challenges associated with scale-up production as well as the necessity for a more thorough understanding of the basic principles of operation will be important to solve [66, 67]. Fig. 5 illustrates carbon nanocomposites for energy storage application.

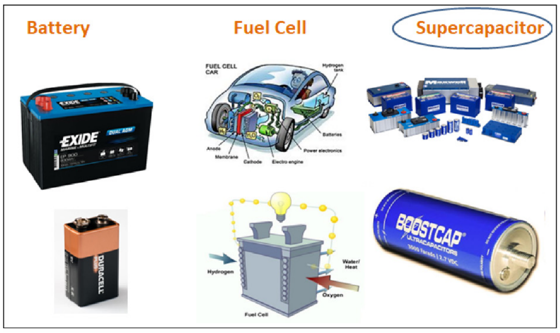

Fig. 5. Carbon nanocomposites for energy storage application [68].

Carbon materials are used in energy storage due to their low cost, light weight, and easy recovery. Carbon materials are essential in capacitors, such as activated carbon/porous carbon/graphene for capacitive-type cathodes, graphite/graphene/disordered carbon/N-doped carbon nanotubes for battery-type anodes, and graphite oxide for gel electrolyte fillers [69, 70]. The capacitor cathode needs several active carbon sites for reversible anion adsorption/desorption. The battery-type anode needs extended interlayer spacing for reversible insertion/extraction of massive Na^+, K^+, or Zn^{2+} ions. Additionally, oxygen-containing functional groups on carbon increase capacitance and interlayer separation, improving K diffusion [71]. Carbon-based nanocomposites have emerged as the most promising materials in nanoscience and technology in recent years. A variety of techniques have been employed to fabricate carbon-supported nanocomposites, particularly sol–gel, microwave-assisted, sonochemical, electrochemical, and hydrothermal processes. The electrochemical approach is promising due to various advantages, including reduced production time, uniform and desirable layer thickness, and enhanced stability [72]. Over the past decade, carbon composites have significantly influenced the domain of transdisciplinary research and technology. Due to its environmentally friendly and cost-effective nature, along with exceptional chemical, mechanical, electrical, and surface qualities, carbon composite electrodes are widely utilized in energy storage applications [73].

Carbon oxide and carbon sulfide nanocomposites have garnered significant attention as anode materials for lithium and sodium ion batteries. These composites are intriguing as they frequently exhibit a synergistic effect in comparison to their individual components. Carbon nanotubes are frequently employed as the matrix owing to their superior conductivity, tensile strength, and chemical stability under battery conditions. Metal oxides and sulfides are frequently employed as active material fillers due to their substantial capacity. Extensive research indicates that advancing the fabrication of nanocomposites through strategic structural design can significantly enhance performance [74, 75]. Moreover, CNTs, possessing a large specific surface area (albeit comparatively lower than activated carbons), and characterized by a well-defined hollow core, are appealing electrode materials for supercapacitors. Carbon nanotubes (CNTs) have been utilized as electrodes or conductive additives in composite electrodes with activated carbons (ACs), conjugated polymers, or metal oxides. In comparison to ACs, CNTs exhibit superior electrical conductivity, microporosity, and electrolyte accessibility [76]. Recent developments in nickel-based supercapacitors have concentrated on their composites with carbon nanomaterials. These composites exhibit better electrical conductivity, increased surface area, and superior electrochemical performance by resolving significant challenges associated with cycling stability and low energy density. Fig. 1 illustrates the benefits of supercapacitors and the characteristics of carbon nanomaterials utilized as supercapacitor electrodes. Fig. 6 illustrates various types of nickel materials and carbon nanostructures used in supercapacitors [77].

Different forms of carbon-based composite electrodes, including CAs, CNFs, fullerenes, SWCNTs, MWCNTs, and GR, have been shown to serve as effective candidates for fuel cell catalysts. The capacity to customize the properties of these intriguing materials, particularly their electrical attributes, to meet the distinct demands of each application holds significant potential for advancements in this innovative field [72]. Furthermore, the elevated electronic conductivity of these materials poses a limitation for their utilization in Methanol Fuel Cells (PEMs), where it is disadvantageous. Recent review articles focusing on the application of carbonaceous materials in fuel cells, particularly graphene oxide, are limited [26,27,28]. You et al. [78] examine the utilization of CNTs, fullerene, graphene, carbon nanofibers, aerogel, nanocoils, carbon black, and mesoporous carbon as additives in electrodes and membranes for fuel cells is inherently overly broad. Conversely, the reviews by Panday et al. [79] are limited to the utilization of GO fillers as a polymer electrolyte membranes (PEM). Table 1. demonstrates summary of research on carbon nanocomposites for energy storage applications conducted from 2020 to 2024.

5. Advanced application of carbon nanocomposites sensors and biosensors

Carbon nanomaterials and their nanocomposites, have been extensively incorporated with various sensing electrode materials for biomarker detection across diverse experimental conditions [98]. Electrochemical sensors and biosensors have garnered significant interest for the precise detection of diverse biological and pharmacological substances.

Following the discovery of carbon-based nanomaterials, such as carbon nanotubes, graphene, and C60, there has been significant interest in their application for developing high-performance electrochemical sensor platforms, owing to their remarkable electronic, mechanical, thermal, and catalytic properties. Electrochemical sensors based on carbon nanomaterials have been utilized for the detection of several analytes, exhibiting fast electron transfer kinetics [98, 99]. Schedin et al. demonstrated the first graphene-based gas sensor in 2007 [100] , demonstrating micrometre-sized graphene sensors that can detect individual gas molecules that attach to or detach from the graphene surface. They found that adsorbed molecules modify graphene's local carrier concentration one electron at a time, causing step-like resistance changes.

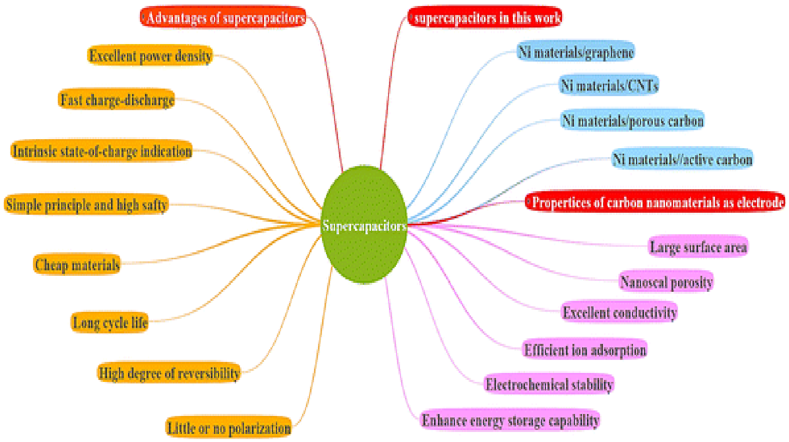

Fig. 6. Benefits of supercapacitors and the characteristics of carbon nanomaterials as supercapacitor electrodes [77].

Table 1
Summary of research on carbon nanocomposites for energy storage applications.

Nanocomposite	Method	Applications	Ref.
S/C nanocomposite	Novel facile route	Lithium-ion batteries	[80]
MoO_2@CNT nanocomposite	Electrical explosion	Lithium–sulfur batteries	[81]
RGO–CNT nanocomposite	Simple one-step protocol	Lithium-ion batteries	[82]
P-CD/G nanocomposites	Biomass-derived method	All-Solid-State Flexible Al–Air Batteries	[83]
$CuSi_2P_3$@Graphene nanocomposite	High-energy ball milling	Lithium-ion batteries	[84]
f-CNT/PANI nanocomposite	In-situ polymerization	Zinc-ion batteries and zinc-ion hybrid supercapacitors	[85]
COF/CNT nanocomposite	Facile strategy of functional coated separator	Lithium–sulfur batteries	[86]
PVDF/CNTs-PT @ Zn nanocomposite	A phase transfer method	Zinc-Ion Batteries	[87]
GNP-CNT-ZrO_2 nanocomposite	Simple hydrothermal method	Lithium-ion batteries	[88]
titania/graphene nanocomposite	Sol–gel	Li-ion batteries	[89]
SWCNT/ZnO nanocomposite	Attaching carbon dots (CDs)	Photoresponsive supercapacitor	[90]
Nickel ferrite@MWCNTs nanocomposite	Sol–gel	Supercapacitor	[91]
mSiO 2 @rGO nanocomposite	Sol–gel	Superior lithium-ion capacitor	[92]
NiO/CNT nanocomposite	H_2O_2-assisted microwave irradiation	supercapacitor	[93]
NiFe@CNTs nanocomposite	Catalytic pyrolysis of waste plastics	Low-temperature solid oxide fuel cells	[94]
polymer/MWCNT nanocomposite	Solution processing	High-temperature PEM fuel cells	[95]
Fe_x-CNT@NHC nanocomposite	Simple and robust preparation	Alkaline fuel cellS	[96]
CNT-*g*-PAA@SnO_2/PtRu nanocomposite	Newly hierarchical quaternary	direct methanol fuel cells	[97]

Electronically, graphene is very low-noise, making it a promising material for chemical detectors and other applications that require local probes sensitive to external charge, magnetic field, or mechanical strain.

The recent discovery of carbon nanotubes has garnered significant attention due to their size and structure-sensitive characteristics. The elevated electrical conductivity of these nanostructures facilitates the use of CNTs as electrode material, and in conjunction with their robust electrocatalytic activity, enables the mediation of electron transfer reactions[101, 102]. The capability of electron transfer between electroactive species and the electrode holds significant potential, particularly for the development of chemical sensors. According to Jacobs et al. [103], the distinctiveness of CNTs enhances electronic characteristics, increases the edge plane/basal plane ratio, and accelerates electrode kinetics. Consequently, CNT-based sensors typically exhibit superior sensitivity, reduced limits of detection (LOD), and accelerated electron transfer kinetics compared to conventional carbon electrodes.

Moreover, carbon-based quantum dots, in contrast to other prevalent quantum dots, exhibit solubility in aqueous solutions and possess non-toxic characteristics. carbon quantum dots (CQDs) and graphene quantum dots (GQDs) -based nanocomposites (NCs) are distinguished by surface imperfections and superior optical characteristics, rendering them suitable for application as sensors for the identification and elimination of toxic contaminants, respectively. The LOD for GQD and CQDs is at nanomolar, picomolar, or even femtomolar concentrations, rendering them appropriate for precision sensor systems. Numerous types of sensors, such as chemiluminescence, photoluminescence, and electrochemiluminescence, exist, as shown in Fig. 7 [104].

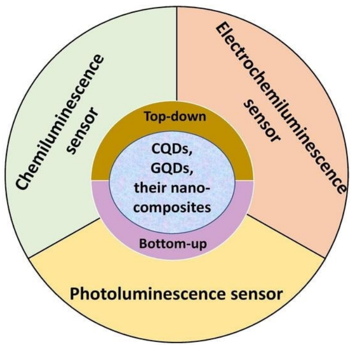

Fig. 7. Numerous types of sensors [104].

In addition to zero-dimensional and two-dimensional carbon nanomaterials, one-dimensional carbon nanofibers have also emerged as potentially useful platforms for applications in the field of biosensing. Non-enzymatic biosensors utilizing CNF nanocomposites are generally constructed with nanoparticles of platinum, copper, cobalt, nickel, copper oxide, cobalt oxide, and nickel oxide. Liu et al. [105] introduced a glucose biosensor utilizing Ni nanoparticle-embedded CNF electrodes by the integration of electrospinning and thermal processing. Due to the extensive surface area of CNF and the elevated electrocatalytic activity of Ni nanoparticles, the CNF/Ni electrode demonstrated exceptional electrocatalytic performance for glucose oxidation. Zhang et al. [106] demonstrated a nanocomposite of nano-cupric oxide (CuONPs) on a CNF surface for the development of a non-enzymatic glucose biosensor. The conductive substrate of CNFs facilitates rapid electron transmission, allows CuONPs to distribute on their surface, and serves as a supporting matrix that inhibits the detachment of nanoparticles from the electrode surfaces. The findings of this work demonstrate that CuONPs serve as a potent electrocatalyst for glucose oxidation, hence improving the efficacy of the biosensor. According to research by K Murtada, et al. a sensitive and selective voltammetric eugenol measurement was performed on several samples using a modified glassy carbon electrode (CuSe/rGO/GCE). The decreased graphene oxide was covered with CuSe/rGO utilizing supercritical carbon dioxide. It reduces GO sheets to scatter CuSe nanoparticles due to its gas-like diffusivity, exceptionally low viscosity, and good penetration. Encapsulating with graphene holes prevents catalytically active NPs from aggregating. The synthesized CuSe/rGO composite modified GCEs. This sensor has a linear dynamic range of 1μg/kg to 82μg/kg, a LOD of 0.41μg/kg, and recoveries of 88.5% to 94.8% [107].

6. Biomedical applications of carbon nanocomposites

Carbon nanomaterials have been extensively studied for biological applications due to their electrical conductivity, biocompatibility, and optical characteristics. CDs are carbon nanoparticles under 10 nm in size, characterized by exceptional photoluminescence properties, biocompatibility, low toxicity, and a notable quenching effect, enabling them to emit their own fluorescent signal, thus rendering them a compelling option for bioimaging and drug delivery applications [108]. Carbon nanocomposites, characterized by low toxicity and other advantages such as economical manufacture, excellent mechanical stability, robust biocompatibility, biodegradability, and antibacterial properties, have garnered significant interest from researchers [109].

Graphitic carbon nitride, characterized by a 2D nanosheet structure, possesses considerable potential as a functional element in nanocarriers due to its remarkable attributes, including elevated thermal and chemical durability, favorable biocompatibility, and enhanced tissue permeability. The vast surface area of graphitic carbon nitride facilitates effective drug encapsulation. A study exemplifying the advantageous features of graphitic carbon nitride involved the development of a pH-sensitive nanocarrier, comprising chitosan, agarose, graphitic carbon nitride, and curcumin, designed to deliver curcumin to breast cancer cells [110].

Moreover, CNT nanocomposite possesses intrinsic antimicrobial characteristics that function as antibacterial agents in wound healing, either to intermolecular interactions or the formation of reactive oxygen species (ROS). For instance, in a CNT@MoS_2 NSs integrated PVA/sodium alginate (PSCMo) hydrogel, CNTs infused with MoS_2 NSs markedly enhanced the nanozyme activities of MoS_2 via NIR irradiation. In an antibacterial assessment, CNT@MoS_2 nanosheets containing 20 wt% CNT exhibited superior antibacterial efficacy, attributed to their optimal photothermal conversion capability and peroxidase-like activity [111]. Hydrogel wound dressings utilizing various carbon nanomaterials have been persistently created, as illustrated in Fig. 8. (a) The chronology of the initial production of hydrogel wound dressings employing various carbon-based nanomaterials. (b) Depiction of multifunctional carbon-based nanocomposite hydrogels [112].

In accordance with this study, more research has shown CNT-based nanocomposites for medication delivery and phototherapy. CNTs demonstrate significant absorption in the near-infrared (NIR) spectrum, specifically between 750 nm and 1400 nm, and possess the capability to transform NIR light into localized thermal energy. Utilizing these features, a mesoporous silica (MS)-modified CNT nano-platform was developed in one study [113]. Recent research indicates that optimizing the characteristics of CNTs enables both medication and gene delivery. A nanocarrier based on MWCNT/Fe_3O_4 was created for the simultaneous delivery of medicines and genes [114]. In recent years, carbon nanomaterials have exhibited promise in tissue engineering, including scaffold design, mechanical support, cellular contact, and regeneration, due to their unique physicochemical characteristics. Investigations are being conducted to develop tissue-specific scaffolds for transplantation with carbon nanomaterials. This text discusses recent studies on tissue engineering utilizing carbon-based nanocomposites. Carbon - based nanocomposites have been researched for cell differentiation due to their unique structural and physiochemical features. The functional groups of carbon nanomaterial-based nanocomposites can easily be coupled with other biomaterials that stimulate cell differentiation, which was used to control stem-cell differentiation. CNT-modified polycaprolactone (PCL) nanofibers modulate numerous cell interactions [115]. Table 2 illustrates several recent research of carbon-based nanocomposite for biomedical applications.

7. Conclusion

In this review is investigated recent research trends and results that are focused on application of carbon-based nanocomposites multifunctional. Many of the carbon nanostructures (i.e., graphene, carbon nanotubes, carbon nanofibers) mentioned previously show a synergistic effect among other classes of materials, including metals, polymers and ceramics, to produce improvements in the electrical conductivity, mechanical strength, surface reactivity and functional stability of the final composite. The applications of carbon nanoparticles for battery and capacitor architectures will provide improvements in energy storage solutions by increasing the rate of charge transport, increasing the specific surface area and increasing the electrochemical stability. In addition, using carbon matrices integrated with an interpenetrating phase of redox-active materials have been shown to reduce the volume expansion experienced during cycling, improve cycling stability and increase scalability for the design of electrodes. Carbon-based nanocomposites are highly sensitive and may be tailored to improve their surface chemistry for compatibility with biomolecular recognition components, making them advantageous for use in the development of chemical and biological sensing/biosensing technologies.

They have a low limit of detection, short response times and high selectivity toward chemical species and biomolecules. Applications include environmental monitoring, health diagnostics and wearable sensor technologies. When viewed from a structural and engineering point of view, carbon nanocomposites include a multitude of capabilities. These characteristics include higher mechanical strength, improved electrical conductivity, increased thermal stability, and resistance to corrosion. These characteristics make these materials especially useful in smart materials, structural health monitoring systems, as well as for next-generation functional coatings. All of the studies reviewed to date show that carbon nanocomposites can be developed as an extremely versatile and powerful material platform and can be designed rationally with new techniques to overcome performance limitations in a wide range of applications.

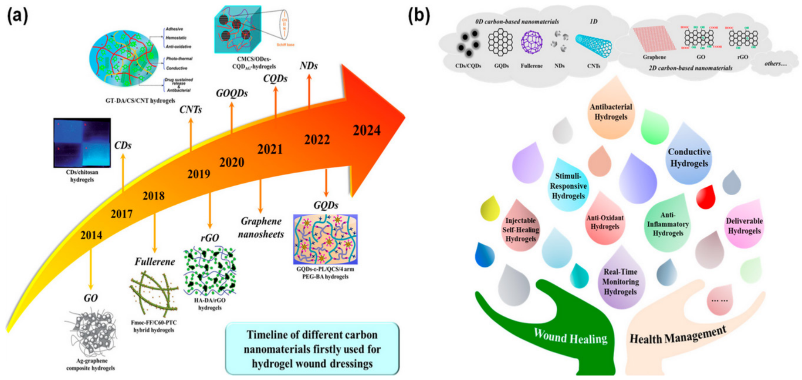

Fig. 8. Multifunctional carbon-derived hydrogel dressings [112].

Table 2
Several recent research of carbon-based nanocomposite for biomedical applications.

Nanocomposite	Application	Result	Ref.
PHB-Chitosan/MWCNTs nanocomposite	Tissue engineering	PHB-Chitosan/MWCNTs nanocomposite coating increases MG-63 cell proliferation, viability, and alkaline phosphatase secretion.	[116]
HAP-MWCNT and HAP-GO NCs nanocomposites (MWCNTs, GO =0.5, 1 and 2 wt%)	Tissue engineering	Adding CNTs did not affect desorption efficiency, while adding GO increased it over time for all NCs.	[117]
PP/n-HA/f-MWCNTs nanocomposites	Orthopedics applications	Tensile experiments showed that f-MWCNTs increase the tensile strength of PP/n-HA nanocomposites but lower their Young's modulus.	[118]
MZ/GNPs + CNTs composites	Bone infection treatment	The MTT with 0.5 and 1 wt % GNPs + CNTs did not cytotoxically affect MG63 cells, while excessive GNPs + CNTs are toxic. I	[119]
CS/PVA/CS-g-CNO nanocomposite	Tissue regeneration	After 25 days, films degraded into simulated bodily fluid (SBF) losing 14%–16% of their initial weight. Composites of CS-g-CNO degraded faster (weight loss and pH changes) due to greater hydrogen bonding SBF interaction.	[120]
NFP-MWCNT and NFB-MWCNT nanocomposite	Wound-healing	The results indicated that NFB-MWCNT and NFP-MWCNT cells healed well. The heteroatoms' differing electronegativity provides a surface charge that limits biofilm formation, and heals wounds.	[121]
CS-CQD-TiO_2-GO nanocomposite	Wound dressing	Tensile strength and elongation testing demonstrated that the nanofibrous mat is flexible and strong enough for wound treatment.	[122]
ZnO/GO nanocomposite	Wound healing	The scaffolds' mechanical properties showed significant variations in tensile strength and toughness. In addition, ZnO/GO@CA revealed a cell viability advancement of 97.38 ± 3.9%.	[123]
GO /Au nanocomposite	Chemo and photothermal therapy	The increase in NIR-induced drug release and photothermal property suggests that the fGO@GNRs-DOX technique is suited for chemotherapy and photothermal therapy.	[124]

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

REFERENCES

[1] S.K. Kumar, R. Krishnamoorti, Nanocomposites: structure, phase behavior, and properties, Annual review of chemical and biomolecular engineering 1(1) (2010) 37–58.
[2] E. Omanović-Mikličanin, A. Badnjević, A. Kazlagić, M. Hajlovac, Nanocomposites: a brief review, Health and Technology 10(1) (2020) 51–59.
[3] L.M. Manocha, J. Valand, N. Patel, A. Warrier, S. Manocha, Nanocomposites for structural applications, Indian Journal of Pure and Applied Physics 44(2) (2006) 135–142.
[4] P.H.C. Camargo, K.G. Satyanarayana, F. Wypych, Nanocomposites: synthesis, structure, properties and new application opportunities, Materials Research 12 (2009) 1–39.
[5] Y. Dzenis, Structural nanocomposites, Science 319(5862) (2008) 419–420.
[6] H. Liu, R. Jian, H. Chen, X. Tian, C. Sun, J. Zhu, Z. Yang, J. Sun, C. Wang, Application of biodegradable and biocompatible nanocomposites in electronics: current status and future directions, Nanomaterials 9(7) (2019) 950.
[7] M. Ul-Islam, M. Wajid Ullah, S. Khan, T. Kamal, S. Ul-Islam, N. Shah, J. Kon Park, Recent advancement in cellulose based nanocomposite for addressing environmental challenges, Recent patents on nanotechnology 10(3) (2016) 169–180.
[8] P.J. Harris, Carbon nanotube science: synthesis, properties and applications, Cambridge university press 2009.
[9] R. Sanjinés, M.D. Abad, C. Vâju, R. Smajda, M. Mionić, A. Magrez, Electrical properties and applications of carbon based nanocomposite materials: An overview, Surface and coatings technology 206(4) (2011) 727–733.
[10] Y. Zhu, Y. Feng, S. Chen, M. Ding, J. Yao, Carbon nitride nanotube-based materials for energy and environmental applications: a review of recent progresses, Journal of Materials Chemistry A 8(48) (2020) 25626–25648.
[11] R. Rao, C.L. Pint, A.E. Islam, R.S. Weatherup, S. Hofmann, E.R. Meshot, F. Wu, C. Zhou, N. Dee, P.B. Amama, Carbon nanotubes and related nanomaterials: critical advances and challenges for synthesis toward mainstream commercial applications, ACS nano 12(12) (2018) 11756–11784.
[12] M. Baibarac, P. Gomez-Romero, M. Lira-Cantu, N. Casañ-Pastor, N. Mestres, S. Lefrant, Electrosynthesis of the poly (N-vinyl carbazole)/carbon nanotubes composite for applications in the supercapacitors field, European polymer journal 42(10) (2006) 2302–2312.
[13] H.M. Fahmy, E.S. Abu Serea, R.E. Salah-Eldin, S.A. Al-Hafiry, M.K. Ali, A.E. Shalan, S. Lanceros-Mendez, Recent progress in graphene-and related carbon-nanomaterial-based electrochemical biosensors for early disease detection, ACS Biomaterials Science & Engineering 8(3) (2022) 964–1000.
[14] S. Zheng, Y. Tian, J. Ouyang, Y. Shen, X. Wang, J. Luan, Carbon nanomaterials for drug delivery and tissue engineering, Frontiers in Chemistry 10 (2022) 990362.
[15] K.P. Gopinath, D.-V.N. Vo, D. Gnana Prakash, A. Adithya Joseph, S. Viswanathan, J. Arun, Environmental applications of carbon-based materials: a review, Environmental Chemistry Letters 19(1) (2021) 557–582.
[16] V.N. Popov, Carbon nanotubes: properties and application, Materials Science and Engineering: R: Reports 43(3) (2004) 61–102.
[17] H. Dai, Carbon nanotubes: opportunities and challenges, Surface Science 500(1) (2002) 218–241.
[18] K. Kobashi, S. Ata, T. Yamada, D.N. Futaba, T. Okazaki, K. Hata, Classification of commercialized carbon nanotubes into three general categories as a guide for applications, ACS Applied Nano Materials 2(7) (2019) 4043–4047.
[19] M.J. Schulz, V.N. Shanov, Nanomedicine design of particles, sensors, motors, implants, robots, and devices, Artech House 2009.
[20] A. Yohannan, S. Vincent, N. Divakaran, A.K. Pottikadavath Venugopal, S. Patra, K. Ashish, S. Mohanty, Experimental and simulation studies of hybrid MWCNT/montmorillonite reinforced FDM based PLA filaments with multifunctional properties enhancement, Polymer Composites 45(1) (2024) 507–522.
[21] W.L. Baloch, R.A. Khushnood, W. Khaliq, Influence of multi-walled carbon nanotubes on the residual performance of concrete exposed to high temperatures, Construction and Building Materials 185 (2018) 44–56.
[22] Y. Li, Y. Sun, J. Yeow, Nanotube field electron emission: principles, development, and applications, Nanotechnology 26(24) (2015) 242001.
[23] A. Ali, S.S. Rahimian Koloor, A.H. Alshehri, A. Arockiarajan, Carbon nanotube characteristics and enhancement effects on the mechanical features of polymer-based materials and structures – A review, Journal of Materials Research and Technology 24 (2023) 6495–6521.
[24] X.X. Wang, J.N. Wang, H. Chang, Y.F. Zhang, Preparation of short carbon nanotubes and application as an electrode material in Li-ion batteries, Advanced Functional Materials 17(17) (2007) 3613–3618.
[25] H. Zare, S. Ahmadi, A. Ghasemi, M. Ghanbari, N. Rabiee, M. Bagherzadeh, M. Karimi, T.J. Webster, M.R. Hamblin, E. Mostafavi, Carbon nanotubes: Smart drug/gene delivery carriers, International Journal of Nanomedicine 16 (2021) 1681–1706.
[26] M. Xu, T. Liang, M. Shi, H. Chen, Graphene-like two-dimensional materials, Chemical Reviews 113(5) (2013) 3766–3798.
[27] A.B. Kaul, Two-dimensional layered materials: Structure, properties, and prospects for device applications, Journal of Materials Research 29(3) (2014) 348–361.
[28] P. Viprya, D. Kumar, S. Kowshik, Study of Different Properties of Graphene Oxide (GO) and Reduced Graphene Oxide (rGO), Engineering Proceedings 37(1) (2023) 84.
[29] A.N. Ghulam, O.A.L. dos Santos, L. Hazeem, B. Pizzorno Backx, M. Bououdina, S. Bellucci, Graphene Oxide (GO) Materials—Applications and Toxicity on Living Organisms and Environment, Journal of Functional Biomaterials 13(2) (2022) 77.
[30] N. Sharma, V. Sharma, Y. Jain, M. Kumari, R. Gupta, S. Sharma, K. Sachdev, Synthesis and characterization of graphene oxide (GO) and reduced graphene oxide (rGO) for gas sensing application, Macromolecular Symposia 376(1) (2017) 1700006.
[31] S.C. Ray, Application and uses of graphene oxide and reduced graphene oxide, Applications of Graphene and Graphene-Oxide Based Nanomaterials (2015) 39–55.
[32] F. Bonaccorso, A. Lombardo, T. Hasan, Z. Sun, L. Colombo, A.C. Ferrari, Production and processing of graphene and 2d crystals, Materials Today 15(12) (2012) 564–589.
[33] R. Sharma, K.K. Kar, Characteristics of carbon nanofibers, Handbook of Nanocomposite Supercapacitor Materials I: Characteristics (2020) 215–245.
[34] Y.A. Kim, T. Hayashi, M. Endo, M.S. Dresselhaus, Carbon nanofibers, Springer Handbook of Nanomaterials (2013) 233–262.
[35] R. Sharma, K.K. Kar, Characteristics of Carbon Nanofibers, in: K.K. Kar (Ed.), Handbook of Nanocomposite Supercapacitor Materials I: Characteristics, Springer International Publishing, Cham (2020) 215–245.
[36] D. Ozyurt, M.A. Kobaisi, R.K. Hocking, B. Fox, Properties, synthesis, and applications of carbon dots: A review, Carbon Trends 12 (2023) 100276.
[37] K. Jiang, S. Sun, L. Zhang, Y. Lu, A. Wu, C. Cai, H. Lin, Red, green, and blue luminescence by carbon dots: full-color emission tuning and multicolor cellular imaging, Angewandte Chemie 127(18) (2015) 5450–5453.
[38] V. Georgakilas, J.A. Perman, J. Tucek, R. Zboril, Broad Family of Carbon Nanoallotropes: Classification, Chemistry, and Applications of Fullerenes, Carbon Dots, Nanotubes, Graphene, Nanodiamonds, and Combined Superstructures, Chemical Reviews 115(11) (2015) 4744–4822.
[39] A.J. Clancy, M.K. Bayazit, S.A. Hodge, N.T. Skipper, C.A. Howard, M.S.P. Shaffer, Charged Carbon Nanomaterials: Redox Chemistries of Fullerenes, Carbon Nanotubes, and Graphenes, Chemical Reviews 118(16) (2018) 7363–7408.
[40] Z. Qi, H. Zhang, A note on the cyclical edge-connectivity of fullerene graphs, Journal of Mathematical Chemistry 43(1) (2008) 134–140.
[41] X. Zhang, N. Zhao, C. He, The superior mechanical and physical properties of nanocarbon reinforced bulk composites achieved by architecture design–a review, Progress in Materials Science 113 (2020) 100672.
[42] S.Z. Al Sheheri, Z.M. Al-Amshany, Q.A. Al Sulami, N.Y. Tashkandi, M.A. Hussein, R.M. El-Shishtawy, The preparation of carbon nanofillers and their role on the performance of variable polymer nanocomposites, Designed monomers and polymers (2019).
[43] F.S.A. Khan, N. Mubarak, M. Khalid, M.M. Khan, Y.H. Tan, R. Walvekar, E. Abdullah, R.R. Karri, M.E. Rahman, Comprehensive review on carbon nanotubes embedded in different metal and polymer matrix: fabrications and applications, Critical Reviews in Solid State and Materials Sciences 47(6) (2022) 837–864.

[44] S. Tamayo-Vegas, A. Muhsan, C. Liu, M. Tarfaoui, K. Lafdi, The Effect of Agglomeration on the Electrical and Mechanical Properties of Polymer Matrix Nanocomposites Reinforced with Carbon Nanotubes, Polymers, 2022, p. 1842.
[45] R. Dubey, D. Dutta, A. Sarkar, P. Chattopadhyay, Functionalized carbon nanotubes: synthesis, properties and applications in water purification, drug delivery, and material and biomedical sciences, Nanoscale Adv 3(20) (2021) 5722–5744.
[46] M.C. Paiva, B. Zhou, K.A.S. Fernando, Y. Lin, J.M. Kennedy, Y.P. Sun, Mechanical and morphological characterization of polymer–carbon nanocomposites from functionalized carbon nanotubes, Carbon 42(14) (2004) 2849–2854.
[47] O.K. Abubakre, R.O. Medupin, I.B. Akintunde, O.T. Jimoh, A.S. Abdulkareem, R.A. Muriana, J.A. James, K.O. Ukoba, T.-C. Jen, K.O. Yoro, Carbon nanotube-reinforced polymer nanocomposites for sustainable biomedical applications: A review, Journal of Science: Advanced Materials and Devices 8(2) (2023) 100557.
[48] B. Huang, Carbon nanotubes and their polymeric composites: the applications in tissue engineering, Biomanufacturing Reviews 5(1) (2020) 3.
[49] N. Mohd Nurazzi, M.R.M. Asyraf, A. Khalina, et al., Fabrication, Functionalization, and Application of Carbon Nanotube-Reinforced Polymer Composite: An Overview, Polymers, 2021, p. 1047.
[50] S.E. Shin, H.J. Choi, J.Y. Hwang, D.H. Bae, Strengthening behavior of carbon/metal nanocomposites, Scientific Reports 5(1) (2015) 16114.
[51] M. Huda, M. Hashmi, M. El-Baradie, MMCs: materials, manufacturing and mechanical properties, Key engineering materials 104 (1995) 37–64.
[52] L. Singh, B. Singh, K.K. Saxena, Manufacturing techniques for metal matrix composites (MMC): an overview, Advances in Materials and Processing Technologies 6(2) (2020) 441–457.
[53] Z. Zhang, A. Yuvaraj, J. Di, S. Qian, Matrix design of light weight, high strength, high ductility ECC, Construction and Building Materials 210 (2019) 188–197.
[54] A. Osman, A. Elhakeem, S. Kaytbay, A. Ahmed, A comprehensive review on the thermal, electrical, and mechanical properties of graphene-based multi-functional epoxy composites, Advanced Composites and Hybrid Materials 5(2) (2022) 547–605.
[55] X. Huang, Z. Yin, S. Wu, X. Qi, Q. He, Q. Zhang, Q. Yan, F. Boey, H. Zhang, Graphene-based materials: synthesis, characterization, properties, and applications, small 7(14) (2011) 1876–1902.
[56] K.S. Novoselov, A.K. Geim, S.V. Morozov, D.-e. Jiang, Y. Zhang, S.V. Dubonos, I.V. Grigorieva, A.A. Firsov, Electric field effect in atomically thin carbon films, science 306(5696) (2004) 666–669.
[57] S.C. Tjong, Recent progress in the development and properties of novel metal matrix nanocomposites reinforced with carbon nanotubes and graphene nanosheets, Materials Science and Engineering: R: Reports 74(10) (2013) 281–350.
[58] G. Lalet, H. Kurita, J.-M. Heintz, G. Lacombe, A. Kawasaki, J.-F. Silvain, Thermal expansion coefficient and thermal fatigue of discontinuous carbon fiber-reinforced copper and aluminum matrix composites without interfacial chemical bond, Journal of materials science 49(1) (2014) 397–402.
[59] S. Rul, F. Lefèvre-schlick, E. Capria, C. Laurent, A. Peigney, Percolation of single-walled carbon nanotubes in ceramic matrix nanocomposites, Acta Materialia 52(4) (2004) 1061–1067.
[60] J. González-Julián, P. Miranzo, M.I. Osendi, M. Belmonte, Carbon nanotubes functionalization process for developing ceramic matrix nanocomposites, Journal of Materials Chemistry 21(16) (2011) 6063–6071.
[61] J. Cho, A.R. Boccaccini, M.S. Shaffer, Ceramic matrix composites containing carbon nanotubes, Journal of Materials Science 44(8) (2009) 1934–1951.
[62] E.T. Thostenson, Z. Ren, T.-W. Chou, Advances in the science and technology of carbon nanotubes and their composites: a review, Composites Science and Technology 61(13) (2001) 1899–1912.
[63] A. Azarniya, S. Sovizi, A. Azarniya, M.R. Rahmani Taji Boyuk, T. Varol, P. Nithyadharseni, H.R. Madaah Hosseini, S. Ramakrishna, M.V. Reddy, Physicomechanical properties of spark plasma sintered carbon nanotube-containing ceramic matrix nanocomposites, Nanoscale 9(35) (2017) 12779–12820.
[64] M. Ramezani, A. Dehghani, M.M. Sherif, Carbon nanotube reinforced cementitious composites: A comprehensive review, Construction and Building Materials 315 (2022) 125100.
[65] S. Mao, G. Lu, J. Chen, Three-dimensional graphene-based composites for energy applications, Nanoscale 7(16) (2015) 6924–6943.
[66] L. Ji, P. Meduri, V. Agubra, X. Xiao, M. Alcoutlabi, Graphene-based nanocomposites for energy storage, Advanced Energy Materials 6(16) (2016) 1502159.
[67] D. Veeman, M.V. Shree, P. Sureshkumar, T. Jagadeesha, L. Natrayan, M. Ravichandran, P. Paramasivam, Sustainable development of carbon nanocomposites: synthesis and classification for environmental remediation, Journal of Nanomaterials 2021 (2021) 5840645.
[68] S.S. Siwal, Q. Zhang, N. Devi, V.K. Thakur, Carbon-Based Polymer Nanocomposite for High-Performance Energy Storage Applications, Polymers 12(3) (2020) 505.
[69] Z. Zhai, L. Zhang, T. Du, B. Ren, Y. Xu, S. Wang, J. Miao, Z. Liu, A review of carbon materials for supercapacitors, Materials & Design 221 (2022) 111017.
[70] Y. Duan, C. Li, Z. Ye, H. Li, Y. Yang, D. Sui, Y. Lu, Advances of carbon materials for dual-carbon lithium-ion capacitors: a review, Nanomaterials 12(22) (2022) 3954.
[71] C. Han, X. Wang, J. Peng, Q. Xia, S. Chou, G. Cheng, Z. Huang, W. Li, Recent progress on two-dimensional carbon materials for emerging post-lithium (Na+, K+, Zn2+) hybrid supercapacitors, Polymers 13(13) (2021) 2137.
[72] T.-W. Chen, P. Kalimuthu, P. Veerakumar, K.-C. Lin, S.-M. Chen, R. Ramachandran, V. Mariyappan, S. Chitra, Recent Developments in Carbon-Based Nanocomposites for Fuel Cell Applications: A Review, Molecules 27(3) (2022) 761.
[73] J.G. Manjunatha, B. Uslu, Carbon-Based Composite Materials for Electrodes, Materials 15(14) (2022) 4908.
[74] Y. Zhao, L.P. Wang, M.T. Sougrati, Z. Feng, Y. Leconte, A. Fisher, M. Srinivasan, Z. Xu, A Review on Design Strategies for Carbon Based Metal Oxides and Sulfides Nanocomposites for High Performance Li and Na Ion Battery Anodes, Advanced Energy Materials 7(9) (2017) 1601424.
[75] M.-S. Balogun, Y. Luo, W. Qiu, P. Liu, Y. Tong, A review of carbon materials and their composites with alloy metals for sodium ion battery anodes, Carbon 98 (2016) 162–178.
[76] W. Lu, R. Hartman, L. Qu, L. Dai, Nanocomposite Electrodes for High-Performance Supercapacitors, The Journal of Physical Chemistry Letters 2(6) (2011) 655–660.
[77] G.B. Pour, H.N. Fard, L.F. Aval, D. Dubal, Recent advances in Ni-materials/carbon nanocomposites for supercapacitor electrodes, Materials Advances 4(23) (2023) 6152–6174.
[78] P. You, S. Kamarudin, Recent progress of carbonaceous materials in fuel cell applications: An overview, Chemical Engineering Journal 309 (2017) 489–502.
[79] R.P. Pandey, G. Shukla, M. Manohar, V.K. Shahi, Graphene oxide based nanohybrid proton exchange membranes for fuel cell applications: An overview, Advances in Colloid and Interface Science 240 (2017) 15–30.
[80] S. Batool, M. Idrees, J. Kong, J. Zhang, S. Kong, M. Dong, H. Hou, J. Fan, H. Wei, Z. Guo, Assessment of the electrochemical behaviour of silicon@carbon nanocomposite anode for lithium-ion batteries, Journal of Alloys and Compounds 832 (2020) 154644.
[81] C. Choi, D.-Y. Lee, J.B. Park, D.-W. Kim, Separators Modified Using MoO2@Carbon Nanotube Nanocomposites as Dual-Mode Li-Polysulfide Anchoring Materials for High-Performance Anti-Self-Discharge Lithium–Sulfur Batteries, ACS Sustainable Chemistry & Engineering 8(40) (2020) 15134–15148.
[82] A. Abbasnezhad, H. Asgharzadeh, A. Ansari Hamedani, S. Hayat Soytas, One-pot synthesis of tin chalcogenide-reduced graphene oxide-carbon nanotube nanocomposite as anode material for lithium-ion batteries, Dalton Transactions 49(18) (2020) 5890–5897.
[83] M. Wang, Y. Li, J. Fang, C.J. Villa, Y. Xu, S. Hao, J. Li, Y. Liu, C. Wolverton, X. Chen, V.P. Dravid, Y. Lai, Superior Oxygen Reduction Reaction on Phosphorus-Doped Carbon Dot/Graphene Aerogel for All-Solid-State Flexible Al–Air Batteries, Advanced Energy Materials 10(3) (2020) 1902736.
[84] W. Li, Q. Ma, P. Shen, Y. Zhou, L. Soule, Y. Li, Y. Wu, H. Zhang, M. Logic, Yolk-shell structured CuSi2P3@Graphene nanocomposite anode for long-life and high-rate lithium-ion batteries, Nano Energy 80 (2021) 105506.
[85] X. Li, Y. Li, S. Xie, Y. Zhou, J. Rong, L. Dong, Zinc-based energy storage with functionalized carbon nanotube/polyaniline nanocomposite cathodes, Chemical Engineering Journal 427 (2022) 131799.
[86] J. Wang, W. Qin, X. Zhu, Y. Teng, Covalent organic frameworks (COF)/CNT nanocomposite for high performance and wide operating temperature lithium–sulfur batteries, Energy 199 (2020) 117372.
[87] J. Wang, J. Peng, W. Huang, H. Liang, Y. Hao, J. Li, H. Chu, H. Wei, Y. Zhang, J. Liu, Enabling Stable Zn Anode with PVDF/CNTs Nanocomposites Protective Layer Toward High-Performance Aqueous Zinc-Ion Batteries, Advanced Functional Materials 34(26) (2024) 2316083.
[88] S.I. Ghazanlou, et al., Synthesis of ternary GNP-CNT-ZrO2 nanocomposite as a high-performance anode for lithium-ion batteries, Journal of Industrial and Engineering Chemistry 128 (2023) 209–221.
[89] S. Khanna, et al., In-situ preparation of titania/graphene nanocomposite via a facile sol–gel strategy: A promising anodic material for Li-ion batteries, Materials Letters 300 (2021) 130143.
[90] R. Sinha, N. Roy, T.K. Mandal, SWCNT/ZnO nanocomposite decorated with carbon dots for photoresponsive supercapacitor applications, Chemical Engineering Journal 431 (2022) 133915.
[91] N. Zahra, et al., Fabrication of nickel ferrite@MWCNTs for super-capacitor applications, Journal of Applied Electrochemistry 54(9) (2024) 1969–1981.
[92] S.A. El-Khodary, et al., Mesoporous silica anchored on reduced graphene oxide nanocomposite as anode for superior lithium-ion capacitor, Rare Metals 41(2) (2022) 368–377.
[93] V. Sannasi, et al., H2O2-assisted microwave synthesis of NiO/CNT nanocomposite material for supercapacitor applications, Ionics 26(8) (2020) 4067–4079.

[94] Q. Liu, et al., Nickel-iron nanoparticles encapsulated in carbon nanotubes prepared from waste plastics for low-temperature solid oxide fuel cells, iScience 25(8) (2022) 104855.
[95] M.A. Haque, et al., Synthesis of polymer/MWCNT nanocomposite catalyst supporting materials for high-temperature PEM fuel cells, International Journal of Hydrogen Energy 46(5) (2021) 4339–4353.
[96] L. Chai, et al., Fe7C3 nanoparticles with in situ grown CNT on nitrogen doped hollow carbon cube with greatly enhanced conductivity and ORR performance for alkaline fuel cell, Carbon 174 (2021) 531–539.
[97] Y. Sang, et al., Ultrafine and Highly Dispersed PtRu Alloy on Polyacrylic Acid-Grafted Carbon Nanotube@Tin Oxide Core/Shell Composites for Direct Methanol Fuel Cells, ACS Applied Energy Materials 5(4) (2022) 4179–4190.
[98] B.-R. Adhikari, M. Govindhan, A. Chen, Carbon Nanomaterials Based Electrochemical Sensors/Biosensors for the Sensitive Detection of Pharmaceutical and Biological Compounds, Sensors 15(9) (2015) 22490–22508.
[99] J. Mondal, et al., Carbon Nanotube and Its Derived Nanomaterials Based High Performance Biosensing Platform, Biosensors 12(9) (2022) 731.
[100] F. Schedin, et al., Detection of individual gas molecules adsorbed on graphene, Nature Materials 6(9) (2007) 652–655.
[101] Y. Zhang, et al., Nanocarbon based composite electrodes and their application in microbial fuel cells, Journal of Materials Chemistry A 5(25) (2017) 12673–12698.
[102] Y. Liu, J. Zhang, Y. Cheng, S. Jiang, Effect of carbon nanotubes on direct electron transfer and electrocatalytic activity of immobilized glucose oxidase, ACS Omega 3(1) (2018) 667–676.
[103] C.B. Jacobs, M.J. Peairs, B.J. Venton, Carbon nanotube based electrochemical sensors for biomolecules, Analytica Chimica Acta 662(2) (2010) 105–127.
[104] A. Kaur, et al., Nanocomposites of Carbon Quantum Dots and Graphene Quantum Dots: Environmental Applications as Sensors, Chemosensors 10(9) (2022) 367.
[105] Y. Liu, H. Teng, H. Hou, T. You, Nonenzymatic glucose sensor based on renewable electrospun Ni nanoparticle-loaded carbon nanofiber paste electrode, Biosensors and Bioelectronics 24(11) (2009) 3329–3334.
[106] J. Zhang, et al., In situ growth cupric oxide nanoparticles on carbon nanofibers for sensitive nonenzymatic sensing of glucose, Electrochimica Acta 105 (2013) 433–438.
[107] K. Murtada, et al., Decoration of graphene oxide with copper selenide in supercritical carbon dioxide medium as a novel approach for electrochemical sensing of eugenol in various samples, The Journal of Supercritical Fluids 153 (2019) 104597.
[108] M. Kurian, A. Paul, Recent trends in the use of green sources for carbon dot synthesis–A short review, Carbon Trends 3 (2021) 100032.
[109] C.-H. Kim, S.-Y. Lee, K.Y. Rhee, S.-J. Park, Carbon-based composites in biomedical applications: a comprehensive review of properties, applications, and future directions, Advanced Composites and Hybrid Materials 7(2) (2024) 55.
[110] M. Rajabzadeh-Khosroshahi, et al., Chitosan/agarose/graphitic carbon nitride nanocomposite as an efficient pH-sensitive drug delivery system for anticancer curcumin releasing, Journal of Drug Delivery Science and Technology 74 (2022) 103443.
[111] Y. Li, R. Fu, Z. Duan, C. Zhu, D. Fan, Adaptive hydrogels based on nanozyme with dual-enhanced triple enzyme-like activities for wound disinfection and mimicking antioxidant defense system, Advanced healthcare materials 11(2) (2022) 2101849.
[112] T. Lu, Y. Chen, M. Sun, Y. Chen, W. Tu, Y. Zhou, X. Li, T. Hu, Multifunctional Carbon-Based Nanocomposite Hydrogels for Wound Healing and Health Management, Gels, 2025, p. 345.
[113] B. Li, S. Harlepp, V. Gensbittel, C.J.R. Wells, O. Bringel, J.G. Goetz, S. Begin-Colin, M. Tasso, D. Begin, D. Mertz, Near infra-red light responsive carbon nanotubes@mesoporous silica for photothermia and drug delivery to cancer cells, Materials Today Chemistry 17 (2020) 100308.
[114] M. Bagherzadeh, M. Safarkhani, H. Daneshgar, F. Radmanesh, F. Taghavimandi, A.M. Ghadiri, M. Kiani, Y. Fatahi, N. Safari-Alighiarloo, S. Ahmadi, N. Rabiee, Magnetic carbon–based nanocomposite decorated with palladium complex for co-delivery of DOX/pCRISPR, Journal of Drug Delivery Science and Technology 78 (2022) 103917.
[115] M. Bagherzadeh, A. Aldhaher, S. Ahmadi, N. Baheiraei, N. Rabiee, Carbon-based nanocomposite decorated with bioactive glass and CoNi2S4 nanoparticles with potential for bone tissue engineering, OpenNano 8 (2022) 100102.
[116] M. Parvizifard, S. Karbasi, Physical, mechanical and biological performance of PHB-Chitosan/MWCNTs nanocomposite coating deposited on bioglass based scaffold: Potential application in bone tissue engineering, International Journal of Biological Macromolecules 152 (2020) 645–662.
[117] R. Barabás, E. de Souza Ávila, L.O. Ladeira, L.M. Antônio, R. Tötös, D. Simedru, L. Bizo, O. Cadar, Graphene Oxides/Carbon Nanotubes–Hydroxyapatite Nanocomposites for Biomedical Applications, Arabian Journal for Science and Engineering 45(1) (2020) 219–227.
[118] F.S.A. Khan, N.M. Mubarak, M. Khalid, R. Walvekar, E.C. Abdullah, A. Ahmad, R.R. Karri, H. Pakalapati, Functionalized multi-walled carbon nanotubes and hydroxyapatite nanorods reinforced with polypropylene for biomedical application, Scientific Reports 11(1) (2021) 843.
[119] J. Liu, X. Wang, A. Saberi, Z. Heydari, The effect of Co-encapsulated GNPs-CNTs nanofillers on mechanical properties, degradation and antibacterial behavior of Mg-based composite, Journal of the Mechanical Behavior of Biomedical Materials 138 (2023) 105601.
[120] C.D. Grande Tovar, J.I. Castro, C.H. Valencia, D.P. Navia Porras, J. Herminsul Mina Hernandez, M.E. Valencia Zapata, M.N. Chaur, Nanocomposite Films of Chitosan-Grafted Carbon Nano-Onions for Biomedical Applications, Molecules, 2020, p. 1203.
[121] B. Murugesan, N. Pandiyan, K. Kasinathan, A. Rajaiah, M. Arumuga, P. Subramanian, J. Sonamuthu, S. Samayanan, V.R. Arumugam, K. Marimuthu, C. Yurong, S. Mahalingam, Fabrication of heteroatom doped NFP-MWCNT and NFB-MWCNT nanocomposite from imidazolium ionic liquid functionalized MWCNT for antibiofilm and wound healing in Wistar rats: Synthesis, characterization, in-vitro and in-vivo studies, Materials Science and Engineering: C 111 (2020) 110791.
[122] F. Norouzi, M. Pourmadadi, F. Yazdian, K. Khoshmaram, J. Mohammadnejad, M.H. Sanati, F. Chogan, A. Rahdar, F. Baino, PVA-Based Nanofibers Containing Chitosan Modified with Graphene Oxide and Carbon Quantum Dot-Doped TiO2 Enhance Wound Healing in a Rat Model, Journal of Functional Biomaterials, 2022, p. 300.
[123] A.A. Aly, M.K. Ahmed, Nanofibers of cellulose acetate containing ZnO nanoparticles/graphene oxide for wound healing applications, International Journal of Pharmaceutics 598 (2021) 120325.
[124] M.S. Khan, S. Pandey, M.L. Bhaisare, G. Gedda, A. Talib, H.-F. Wu, Graphene oxide@gold nanorods for chemo-photothermal treatment and controlled release of doxorubicin in mice Tumor, Colloids and Surfaces B: Biointerfaces 160 (2017) 543–552.