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Review Article

Role of Carbon-Based Nanomaterials in Enhancing the Performance of Energy Storage Devices: Design Small and Store Big

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Energy storage is the process of storing previously generated energy for future usage in order to meet energy demands. The need for high-power density energy storage materials is growing across the board. The high ionic transport, superior electronic conductivity, rapid ion diffusion, high current tolerance, etc. are few among the numerous factors that can be considered the versatilities of nanomaterials. This makes the nanomaterials suitable for energy storage applications. According to the allied market research, the global nanotechnology in energy industry was estimated at \$139.7 million in 2020 and is anticipated to hit \$384.8 million by 2030, registering a compound annual growth rate (CAGR) of 10.7% from 2021 to 2030. The extraordinary and improved properties of carbon-based nanomaterials and their tunable surface chemistry authorize them to be used in design of competent high-energy and high-power energy storage devices. Recent research and future progress focus on effective usage of low-dimensional carbon-based nanomaterials for energy conversion and storage systems. In particular, versatile carbon nanomaterials with multifunctional capabilities have attracted incredible attention in different types of batteries, solar cells, fuel cells, supercapacitors, and other energy storage devices. Engineering the carbon-based nanomaterials with efficient energy storage and remarkable conversion ability embraces the promise of creating a new path for their future development. This article reviews the role of few carbon-based nanomaterials in efficiently increasing the competence and dependability of energy storage applications.

1. Introduction

Developing efficient and sustainable technologies for generating and storing energy is becoming increasingly vital as the world's energy demand grows. Moreover, dependable energy generation at the lowest costs has turn out to be important for meeting out present energy supplies. For this purpose, development of low-cost, scalable, efficient, and reliable catalysts is essential. Carbon-based materials have been shown to hold significant promise in improving the performance and reliability of energy storage and conversion devices. After decades of research and development, a collection of nanomaterials has emerged in picture in the field of energy storage. Along with materialization of other materials in energy storage, carbon materials are considered to play vital role as electrode materials, conductive agents, etc. Compared with traditional carbon materials such as graphite and carbon black, carbon nanomaterials consisting of fullerene, carbon nanotubes, and graphene possess exclusive morphologies and exceptional structures and show potential physical, chemical, and electrical properties.

Carbon-based nanomaterials have a variety of chemical compositions and forms. They range from oxides, chalcogenides, and carbides to carbon and elements that create lithium alloys. This includes quantum dots, nanowires, nanotubes, nanobelts, nanoflakes, and nanosheets. These chemically varied nanoscale building blocks can be combined with lithium ions and beyond to create energy storage solutions such as wearable and structural energy storage technology that are not possible with traditional materials. The high surface-to-volume ratio and compatibility with advanced manufacturing techniques such as printing, spray coating, and roll-to-roll assembly of carbon-based nanomaterials pave the way to the creation of wearable, flexible, and foldable energy storage devices [1]. In the field of energy conversion and storage, many studies have focused on the synthesis, characterization, and fictionalization of carbon nanomaterials, as well as their potential applications. Significant efforts have been made to use carbon nanomaterials in the development of high-performance energy converters.

This review focuses on the role of (i) graphene oxide (GO) and reduced graphene oxide (RGO), (ii) carbon nanotubes (CNTs), and (iii) carbon-based quantum dots (CQDs) in enhancing the effectiveness of energy storage in various energy storage devices.

2. Role of Carbon-Based Nanomaterials in Energy Storage

2.1. Graphene Oxide (GO) and Reduced Graphene Oxide (RGO). GO is a yellow solid with hexagonal lattice structure which is the oxidized structure of graphene having carbon, oxygen, and hydrogen in variable ratios. It is a single sheet of graphite oxide with many oxygen-containing groups which give it a variety of unique properties. This makes GO as a suitable material for adaptable applications in energy storage devices such as batteries, capacitors, and fuel cells particularly in improving the efficiency of the electrodes. This in turn improves their energy storage. Being a monoatomic layered substance with oxygen, GO is identified as nonconductive and dispersible in water.

For the reason that GO contains oxygen-based groups, several functional groups can be included on it which leads to tunable mechanical, electrical, thermal, and barrier properties of GO. This allows them to find applications in energy storage applications such as batteries [2], supercapacitors [3], and fuel cells [4].

2.1.1. GO and RGO in Enhancing Performance of Energy Storage Devices. The oxygen-containing groups in GO donate many exclusive characteristics for potential relevance in energy storage devices for it. The functionalization and band gap of GO can be considerably tuned and controlled [5, 6]. This helps to alter physical and chemical properties of GO which improves its energy storage applications [7]. Ye et al. [8] fabricated metal-GO batteries using GO as both the cathode and separator along with metals like Li, Na, Zn, Fe, and Cu through which they converted chemical energy into electricity and accurately controlled the energy output also. Being a rechargeable energy storage device, a lithium-ion battery has maximum energy capacitance. Zhao et al. [9] reduced GO in Li-ion batteries through an electrochemical method and assembled GO-based composite electrodes into cells in Li-ion batteries which were found to be simple as well as effective. In Li-ion batteries, GO is used as electrodes with improved extension cycle life [10] because of its varied chemical and electronic structures which significantly improve their electrochemical performances.

Because of its superior hydrophilic nature, GO can easily be deposited on any surface. Using GO as anode materials in Li-ion batteries is recognized to be useful in improving their electrochemical performance [11]. Even though Li-ion batteries are considered to be one of the most powerful sources used in many of the electronic devices owing to their greater qualities, they face difficulties in the form of thermal runaway and low operating temperatures. Usage of reduced graphene oxide (RGO) with boron nitride (BN) kind of transition metal oxide (Co_3O_4/RGO/h-BN) was found to be one of the appropriate solutions for the above drawback experienced by Li-ion batteries and helps them to operate at high temperatures and to minimize the thermal runaway [12] considerably. Besides in anode, using GO as cathode materials substantially improved their capacity and stability [13]. Nanostructuring the cathode with $LiMnPO_4$, $LiFePO_4$, $LiCoPO_4$, or $LiNiPO_4$ enlarges its surface that improves the energy storage and steadiness of the charge cycles in Li-ion batteries [14].

The Li-sulfur battery is known to be a potential type of battery because they can reach high energy densities. Additionally, the components needed to fabricate them are cost-effective. Above all, sulfur is relatively environment friendly. GO has played a vital role and found to be a significant material in resolving several confrontations faced by Li-sulfur batteries. Lightcap and Kamat [15] and Liu et al. [16] used GO and RGO, respectively, in Li-sulfur batteries as an active electrode material and noticed a considerable improvement in their efficiency and performance. A chemical process to immobilize sulfur and lithium polysulfides on GO was performed by Ji et al. [17] to reduce the capacity fading in rechargeable Li-sulfur batteries and attained a high reversible capacity of 950–1400 $mA\,h\,g^{-1}$. By taking exceptional conductivity and mechanical strength of GO into consideration, a new improved polysulfide adsorption substance in Li-sulfur batteries was fabricated by packaging RGO on boron nitride nanosheets [18] and managed to reach notable electrochemical stability and cycling reversibility of the sulfur-boron nitride-RGO electrode. RGO and the sulfur materials are embedded in a 3D conducting composite network of RGO and polyethylene glycol to form a cathode material for rechargeable Li-sulfur batteries, and an enhanced Coulombic efficiency and extremely stable cycling performance were accomplished [19].

Nanotechnology notably improved the electrical storage capacity of high-capacity devices like supercapacitors compared to their conventional counter parts. Compared to normal capacitors, supercapacitors are capable of stocking up extra energy. This shows the supercapacitors as eye-catching devices for energy storage. Many research studies have been devoted to fetch out the function and influence of GO and RGO as successful electrode materials in supercapacitors [20–22]. Down et al. [23] employed facile screen printing method to fabricate GO-based supercapacitor, and they were capable of producing the supercapacitors having high reproducibility and flexibility with $0.82\,F\,g^{-1}$ capacitive performance. Since energy storage in supercapacitors occurs via redox reactions with their fast ion-exchange capabilities, this makes them particularly attractive in high-power applications [24]. Supercapacitors can be taken as an substitute device for stocking up the energy that have exclusive qualities such as high power densities, bare memory effect, long cycle lifetime, and environmental friendly nature [25]. In supercapacitors, GO plays a vital role as a good electrode material because of its short processing time and higher capacitance [26] with notable power handling capacity [27] which was well supported by a research study carried out by Xu et al. [28] who confirmed that GO may be an improved option as an electrode material in supercapacitors.

Even now, many heads turn towards supercapacitors due to their large power density, high charging-discharging rate, and lengthy cycle life routine, and supercapacitors still remain to be a clean and green potential energy storage device with lot of extended capacities and futuristic scopes. A new type of all-GO device was proposed by Ogata et al. [29] with GO and RGO as both a tunable supercapacitor and a battery based on the working voltage. It is interesting to note that the device functions as a supercapacitor until 1.2 V. At the operating voltage greater than 1.5 V, it performs as a battery by means of redox reaction. Chemical reaction of GO with sodium borohydride yielded RGO which in turn is used to synthesize RGO-zinc-based nanocomposite through in situ chemical reactions [30]. The same was used in supercapacitor energy devices which resulted in better capacitance with high power ($P = 442.5\,W\,kg^{-1}$) and energy storage ($E = 1.66\,Wh\,kg^{-1}$).

Karakoti et al. [31] explored RGO as a binder free electrode material for the supercapacitor. They have reduced GO to obtain RGO by the sinking and leaving process. These RGO-based supercapacitors show an improved areal specific capacitance of $80.2\,mF\,cm^{-2}$ compared to the graphite sheet. Nanohybrids are materials prepared by combining two nanomaterials via chemical bonding. Baig et al. [32] used a meek hydrothermal method and prepared the molybdenum disulfide (MoS_2) with RGO nanohybrids as electrode material for supercapacitors. Careful examination of their physicochemical and electrochemical properties revealed an enhanced electrochemical performance and notable reduction in the impedance of supercapacitor electrodes with capacitance of 297 F/g and with 95.3% retention in capacitance even after 10,000 cycles at 2 A/g.

Fuel cells are energy conversion devices which generate electricity with supply of fuels. In fuel cells, chemical energy is directly converted to electricity which significantly improves their system efficiency. At low temperatures, GO has comparatively high proton conduction which gives the way to them to be widely used as an effective electrolyte in different types of cells and batteries [33]. Membrane fuel cells with GO demonstrate low maximum power density membrane degradation and loss of surface functionalities which are considered an expected advantage in fuel cells [34]. Here, the GO-hydrogen membrane plays two roles, one as an anode catalyst and other as an electrolyte. Yadav et al. [35] showed that the proton exchange membrane fuel cell foisted using graphene yielded improved power density in addition to high ionic conductivity. Farooqui et al. [36] have highlighted the features of GO and some polymer composites and their compatibility with other solvents in fuel cell technology.

GO is high reactive [37], and it is a material with comparatively high proton conductivity, signifying that it is potentially applicable as proton electrolyte in fuel cells. With proton conducting acidic functional groups, GO is found to be suitable as an electrolyte material for polymer electrolyte membrane fuel cells. Bayer et al. [38] prepared GO paper and observed improved power density from $3.7\,mW\,cm^{-2}$ to $79\,mW\,cm^{-2}$ with decreasing membrane thickness of $3\,\mu m$. GO possess a strong hydrophilic nature. As a result, it dissolves well in water. This makes GO as a brilliant material used in electrodes [39] and proton electrolyte in fuel cells [40]. Thus, graphene-based materials especially GO are being used as various components of fuel cells such as fillers, membranes, and proton-conducting electrolytes. In a recent research, chitosan N-RGO nanocomposite anion exchange membranes were prepared by a facile, dispersion-casting procedure in fuel cells. Genipin, which is a water-soluble bifunctional crosslinking reagent, was used in fuel cells to reorganize mechanical weakens of nanocomposite membranes and achieved considerable improvement in terms of efficiency and performance [41].

2.2. Carbon Nanotubes (CNTs). CNTs are cylindrical structured large molecules with 0.7-50-nanometer diameter that consist of hexagonal arrangement of carbon atoms. This is formed by rolling up sheets of a single layer of graphene, and it is known as single-walled CNTs (SWCNTs). Multiple sheets of graphene are rolled up to form multiwalled CNTs (MWCNTs). Right after their discovery in 1991 by Iijima et al., CNTs have been prepared in large scale by various fabrication methods. It is interesting to note that CNTs prepared by various fabrication techniques considerably vary in terms of their structure and properties [42]. By carefully designing them, the CNTs can be used in diverse applications such as electronics, materials science, chemical processing, and energy management. They show amazing properties of strength and thermal and electrical power which allows them to claim a massive attention in many fields especially in energy storage devices and are believed to be a remarkable breakthrough in science and technology.

The hexagonal lattice of carbon within CNTs is responsible for effectively producing electrical charges throughout the tube which guides CNTs to be utilized in energy storage devices such as Li-ion batteries and electrochemical supercapacitors [43]. Apart from their high electrical conductivity, CNTs possess a large surface area and electrochemical stability which build the potential for CNTs t5be brought into picture as a supplemental material for energy conversion and storage devices. In addition to that, CNTs find wide applications in different areas of science and technology due to their exclusive properties and structural characteristics [44]. CNTs have been used in energy storage systems such as alkali metal ion batteries [45], supercapacitors [46], and fuel cells [47]. CNTs are employed as an additive to boost electronic conductivity of cathode and anode materials in supercapacitors and fuel cells [48].

2.2.1. CNTs in Enhancing Performance of Energy Storage Devices. As mentioned previously, Li-ion batteries are gaining extensive interest in various applications including portable electronics and electric vehicles. But in search of light weight and slimmer Li-ion batteries, researchers are trying to find new materials with better properties such as improved battery capacity, enhanced life cycle, and good charge-discharge rates. CNTs are believed to be a suitable nominee to be used in Li-ion batteries. The amalgamation of CNTs as an active Li-ion storage material and anodes leads to reversible Li-ion capacities which actually exceed 1000 m Ah g^{-1}. Usage of free-standing CNT anodes increases the specific energy density by more than 50% [49], and CNT fiber-based electrodes are being widely used in flexible energy storage devices because of their flexibility, less weight, and hidden encapsulation [42]. Since CNTs are well known and outstanding aspirant for incorporation into batteries, they replaced carbon black additives in lithium-ion battery electrodes and achieved comparatively high conductivity and improved capacity [50]. By following electrochemical charge-discharge measurements, Kawasaki and his coworkers [51] found two types of SWCNTs by various techniques and established that the reversible Li-ion storage capacity of metallic SWCNTs is almost 5 times better than their semiconducting counterparts. Forney and his coworkers [52] studied germanium nanoparticle-based electrodes for Li-ion batteries by adding conductive additives of SWCNT and were successful in reducing the charge transfer impedance (approximately 2.5 times), increasing specific capacities (1100 mA h g −1) and rate performance compared to the already reported additives.

Goriparti et al. [53] synthesized germanium nanocrystals with MWCNT composites for Li-ion batteries which exhibited a discharge capacity of approximately 1160 mA h g^{-1} and achieved a better cycling performance with higher capacity retention. Moreover, they proved an excellent rate performance of these electrodes by delivering a specific capacity of around 406 mA h g^{-1} over 400 charge-discharge cycles. A mesoporous material contains nanopores with diameters ranging from 2 to 50 nanometers. Sun et al. [54] have taken lithium titanate nanoclusters in mesoporous form in a system of super aligned CNTs as the frame to hold up a binder-free electrode in Li-ion batteries. They showed that this combination rendered the composite to own high conductivity, flexibility, and mechanical strength along with larger capacity, high rate capability, and extended cycling stability.

Even though Li-sulfur batteries have gained extensive attention for their high theoretical energy density of 2600 Wh kg-1, they need nanostructured carbon-based materials as sulfur host to balance certain limitations such as sulfur's low conductivity and rigorous polysulfide shuttling effect. CNTs are accepted to be a better sulfur host among their counterparts with their unique 1D structure, first-class conductivity, and outstanding flexibility [55], and it was well supported by Wei et al. [56]. Donoro et al. [57] investigated the implementation of MWCNTs in Li-sulfur batteries to reduce capacity fading due to the formation of lithium polysulfide and the low electronic conductivity of sulfur. Capacity retention of a battery is a measure of the capacity of a battery to retain stored energy during a rest period, and it is considered to be an important factor for an extended battery life. 85% capacity retention with an improved electrochemical performance (most excellent catalytic capacity, 21.5 mAh cm^{-2} areal capacity and 1289 mAh g^{-1} specific capacity) has been achieved in Li-sulfur batteries by Zhang et al. [58] through TiO_2-TiN heterostructure.

The sulfurized polyacrylonitrile nanocomposite with CNT was prepared and used as a binder-free cathode in Li-sulfur batteries yielded promoting electrochemical characteristics with elevated initial discharge capacity (1610 mAh g^{-1}) and exceptional cycle stability (1106 mAh g^{-1}) over 500 cycles [59]. A sulfur-nitrogen-doped CNT composite was deliberated as a cathode material for Li-sulfur batteries. It was easy to prepare them because of their better self-weaving performance with increase in sulfur weight ratio inside the electrode. The nitrogen-CNT offered an extremely conductive and mechanically flexible structure with improved electronic conductivity [60]. Recently, an exclusive CNT-encapsulated-sulfur cathode material was designed for Li-sulfur batteries to lessen lithium-polysulfide shuttle, and more stable cycling behavior was revealed [61].

Pan et al. [62] in 2015 used conducting polymers like polyaniline with CNT and prepared composite fiber-based textiles with gel electrolyte. This has given the way to form a slim, lightweight, translucent, and bendable supercapacitor which exhibited a high specific capacitance. Krukiewicz and his coworkers designed CNT films with various numbers of walls (SWCNTs, MWCNTs), thickness, chirality, and surface chemistry and assessed them based on their electrochemical performance. They came to a conclusion that the chirality-defined pristine SWCNTs had viable advantages such as outstanding charge storage capacity, high areal capacitance, extremely high effective surface area, and favored charge-discharge characteristics to be used in supercapacitors [63].

The polyaniline-CNT fiber nanocomposite was fabricated by using liquid-crystal-spun CNT fiber as the ultimate conductive and flexible electrode for supercapacitors. This was investigated by Kim et al. [64]. In their study, they were capable of attaining supercapacitor electrodes with a high electrical conductivity of 14 kS cm^{-1}, good contact properties at the CNT fiber interface, and high capacitance with negligible capacitance. The results obtained in their study highlight the excellence of highly densified CNT fibers in next-generation flexible supercapacitors for realistic wearable applications. CNT yarns and sheets have been identified with promising performance in energy storage devices including supercapacitors [65].

Besides having the fundamental advantage of being a carbon material, CNTs are considered to be a good candidate to be used in fuel cells because of large thermal and electrical conductivity, high mechanical strength, larger surface area, and chemical stability. Improved energy conversion efficiency [66] and high performance [67] have been noted when CNTs are integrated in fuel cells. The catalysts are materials that allow the reaction to continue swiftly and also smoothen the progress of the reaction of oxygen and hydrogen in fuel cells, and CNTs are observed to improve the performance of catalyst in fuel cells [68]. CNTs decorated with platinum nanoparticles were synthesized by Nagelli et al. [69] for proton exchange membrane (PEM) fuel cell applications as inks to serve as electrodes with relatively higher efficiency. The effect of addition of CNTs on the corrosion resistance of conductive polymer coating inside the PEM fuel cell was investigated which confirmed that the inclusion of CNTs enhanced the electrical conductivity and the corrosion resistance of the polymer. The inhibition efficiency of the polymer in the fuel cell was found to be increased with increasing concentration of CNTs in addition to increase in their charge transfer [70].

2.3. Carbon-Based Quantum Dots (CQDs). CQDs also known as carbon dots or graphene quantum dots (GQDs) are typically zero-dimensional quasispherical carbon nanomaterials composed of amorphous to crystalline carbon base. CQDs were fortuitously invented while the attempts were being taken to purify SWCNTs in 2004. It is remarkable to note that CQDs own chemical structure and physical properties analogous to graphene oxide [71]. CQDs are recognized for their miniature size and uncomparable and complimentary features such as fine biocompatibility, exclusive optical properties, electron mobility [72] abundance, eco-friendliness, and their solubility in aqueous solutions [73]. CQDs are economical and plentiful that makes them a growing celebrity as a nanocarbon member [74]. They are monodisperse (will contain nanoparticles of only prescribed size and very few particles of any other radius) spherical nanoparticles containing a carbon-based framework.

CQDs have lot of oxygen-containing amino, hydroxyl, and carboxyl groups on their surface, and they possess controllable physicochemical properties [75] and have surface passivation effects [76]. The huge surface areas, high-quality conductivity, and swift charge transfer of CQDs along with their size/shape-based tunable electronic and chemical structures award them with enormous probability to be used in electrocatalysis [77]. The varied range of remarkable electrochemical properties of CQDs influences their applications in biosensing, bioimaging, optronics, drug delivery, and energy storage devices [78].

2.3.1. CQDs in Enhancing Performance of Energy Storage Devices. Zhao et al. [79] created coaxial structure of graphene quantum dot-coated CNTs as anodes for Li-ion batteries that supplied huge storage sites for lithium ions with larger specific capacity of 700 mAh g^{-1} after 100 cycles and high rate performance. They also demonstrated the vital function of oxygen functional groups of graphene quantum dots in promoting the performance of the anodes in Li-ion batteries. The carboxyl-functionalized GQD coating on hierarchical nanoflake-based CuO electrodes for Li-ion batteries resulted in lesser charge transfer resistance and enhanced electrical conductivity and also prevented the dissolution and agglomeration of the electrode [80]. Yang and his coworkers used facile self-poring method and synthesized ZnO quantum dots of approximately 5 nm size fixed in highly porous carbon nanosheets for Li-ion batteries, and they observed to deliver greater lithium storage properties and are believed to be capable aspirants for next-generation electrodes for Li-ion batteries [81].

Prasath et al. [82] prepared a composite with bismuth oxide and CQD as an anode material in the Li-ion battery. They found that the anode as prepared demonstrated first-class electrochemical activity with a discharge capacity of 1500 mA h g^{-1}. The cathode materials of Li-ion batteries undergo rapid capacity fading and poor high-rate performance that leads to self-aggregation, dissolution, and fast increased charge transfer resistances. When the anode materials are concerned, low Coulombic efficiency and safety issues are widespread. CQDs emerged as a better material to deal with the above shortcomings faced by the electrode materials of Li-ion batteries [83]. Fernando et al. [84] investigated the performance of Li-ion batteries by employing ZnO quantum dots affixed in amorphous carbon multilayered sheets as electrodes and observed a high reversible capacity of 1015 mA h g^{-1} after 80 cycles with very low capacity fading of only 5.7% along with elevated reversible capacity and long-term stability. Brilliant electrochemical characteristics for an anode material in Li-ion batteries with an improved reversible discharge capacity of 934 mA h g^{-1} even after 50 cycles were obtained by Jing et al. [85] through the quantum dot-coated Mn_3O_4 composite.

Li-sulfur batteries are cost-effective and anticipated to deliver considerable specific energy and accepted to play a vital role towards the rapid development of clean energy [86]. Several excellent literature works have highlighted quantum dots in supercapacitors, lithium-sulfur batteries, and photocatalytic hydrogen production. Park et al. [87] reported that the inclusion of GQDs into the sulfur cathode noticeably improved the utilization of sulfur which gifted high performance, speedy charge transfer, excellent cycling, and rate performance of cathodes in Li-sulfur batteries. In Li-sulfur batteries, shuttling and slow alteration of polysulfides to solid lithium sulfides reduce the full utilization of active materials. To overcome this drawback, Xu et al. [88] employed black phosphorus quantum dots as electrocatalysts in Li-sulfur batteries, and they illustrated the high adsorption and improved polysulfide conversion. Here, the porous carbon-sulfur cathodes exhibit rapid reaction kinetics and no shuttling of polysulfides, permitting a low capacity fading rate and high areal capacities.

Hu et al. [89] used polyethylenimine-CQDs in order to improve the performance of the Li-sulfur batteries to be operated under high current density circumstances with high sulfur loadings. They achieved strong chemical binding and fast ion transport in the as-prepared cathodes, and they delivered a reversible areal capacity of 3.3 mAh cm^{-2} over 400 cycles. TiO_2 quantum dots were grown by Gao and his coworkers [90]. Here, the quantum dots played the role of spacers in Li-sulfur batteries and offered better electrode-electrolyte contact area and improved sulfur loading. The superior adsorption energy of polysulfides with TiO_2 is found to retain on-site polysulfide, speedy ion-electron diffusion, brilliant flexibility, and good cyclability which reveal a better opening for stable Li-sulfur batteries.

Supercapacitors are considered to be one of the eye-catching charge storage devices and attracted a lot of concentration due to their striking properties such as first-class security, brilliant power density, less maintenance cost, and fast charging. And CQDs are being extensively used in electrodes of supercapacitors to improve their energy density [91]. CQDs in the form of both as a bare electrode or composite offer a new way to improve supercapacitor performances in higher specific capacitance and offer a higher energy density and good durability with longer life cycles [92]. Qing et al. [93] framed well crystallized GQDs to boost the electrochemical performance of activated carbons in supercapacitors. The as-formed network considerably improved the charge transfer and ion passage kinetics of the activated carbon. Consequently, the GQD-activated carbon pair achieved an extraordinarily high electric double-layer capacitance of 388 F g^{-1} along with better rate performances which gave the confidence to the researchers to use porous carbon materials for efficient energy storage.

Apart from Li-ion batteries, bismuth oxide and CQD composite electrode was used in supercapacitors also, and they exposed good reversibility and a high specific capacity and delivered an utmost energy density of 88 Wh kg^{-1} [82]. Zhang et al. [94] fabricated purified GQDs and used them as electrode materials for supercapacitors, and it showed an elevated capacitance of 296.7 F g^{-1}, reasonable energy density of 41.2 W h kg^{-1}, and a low internal resistance. Chen et al. [95] fabricated CQDs with C_{60} by potassium hydroxide to form high-density electrodes for supercapacitors which yielded a larger volumetric capacitance of 157.4 F cm^{-3} along with high areal capacitance.

By adding suitable additive materials, GQDs can be used in fuel cells for their enhanced performance [96]. Generally, platinum-based electrocatalysts are used for oxygen reduction reaction in fuel cells. In order to overcome the drawbacks of platinum-based electrocatalysts such as their less availability and high cost, Fei et al. [97] synthesized GQDs from cheap and largely existing coal by hydrothermal treatment and framed hybrid nanoplatelets and reached better electrical conductivity and larger surface area that made the as-prepared electrocatalysts suitable for Li-sulfur batteries. Designing competent and strong oxygen reduction reaction electrocatalysts is believed to play a crucial role in microbial fuel cells. Scientists from Texas already have shown that GQDs clutched on graphene platelets increased the desired characteristics of graphene sheet, building them as a better catalyst than platinum to be used in polymer electrolyte membrane fuel cells [98]. Recently, Yan et al. [99] fabricated B-doped GQDs fixed into the bimetallic organic framework which considerably improved their conductivity. They can reach out more number of catalytic sites and attain low charge transfer resistance. The utmost power density of 703.55 mW m^{-2} has been accomplished which is found to be approximately double the time compared to that of their existing counterparts.

3. Conclusion

In this article, we summarize the impact of some superior carbon-based nanomaterials (GO, RGO, CNTs, and CQDs) in enhancing the efficiency of energy storage devices such as Li-ion, Li-sulfur batteries, supercapacitors, and fuel cells. Energy and environment are chief universal problems leading to environmental pollution. Production of energy from fossil fuels leads to global warming which is a major threat that the world is facing now a days. Hence, present-day researchers are turning their attention to energy storage solutions. Nanotechnology is one of the major fields that play a prominent role in the applications for innovative approaches to energy-efficient storage keeping green engineering of environmental friendly materials in mind. Current investigations and development are focused mainly on the development and upgradation of rechargeable energy storage devices. Above all, energy storage is the base for the upcoming wearable technologies and also the immediate requirement of the world because of serious reliance on electric appliances. With their interesting, tunable, and suitable properties, carbon-based nanomaterials show great potential for energy storage technologies. The use of carbon-based nanomaterials in energy usage is being researched and tried to improve the efficiency of cost-effective, rechargeable energy storage devices such as batteries, supercapacitors, and fuel cells. With the rising demands for small, lightweight, and long-lasting portable electronics, the need for energy storage devices with both large power and large energy densities becomes vitally important. Hence, the entire energy storage research is looking for further advancements in effectively managing the carbon-based nanomaterials, as marvel materials will continue to grow promptly, leading ultimately to a variety of efficient energy storage devices that would help the human fraternity.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

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