Empowering Energy Storage using Graphene and its Derivatives

Abstract:

Graphene, a two-dimensional carbon-based material, holds significant promise for elevating the performance of energy storage technologies such as batteries, supercapacitors, and fuel cells. This review article aims to present the latest advancements in utilizing graphene for energy storage devices, with a focus on developments occurring in the past few months. These advancements involve the integration of graphene-based materials into the device designs to augment their efficiency, longevity, and stability, ultimately driving the evolution of advanced energy storage systems. Realizing graphene's full potential as an energy storage material and comprehending its intrinsic properties necessitate further in-depth investigation. Achieving a comprehensive understanding of graphene is imperative before fully harnessing its capabilities in this field.

Keywords: *Graphene; energy storage; batteries; supercapacitors; fuel cells; high surface area; renewable energy;*

Introduction:

The increasing global energy demand necessitates the development of energy storage systems, including batteries, supercapacitors, and fuel cells. However, the functionality of these devices may be constrained by the materials used in their fabrication. Graphene, a two-dimensional carbon-based material, has shown significant potential in recent years for enhancing the efficiency of these devices. Graphene's remarkable electrical, mechanical, and thermal qualities render it a highly suitable contender for a diverse array of applications, encompassing energy storage devices, owing to its extraordinary electronic, mechanical, and thermal features (Du, Y. et al., 2023). The escalating demand for energy and the expanding use of renewable energy sources have created a pressing want for energy storage systems that exhibit high efficiency and reliability. Batteries, supercapacitors, and fuel cells are regarded as very promising technology for energy storage. The performance of these devices is substantially affected by the choice of materials during their production, as these materials introduce constraints on their operational capabilities. The limitations of current energy storage technologies in terms of storage capacity, efficiency, and durability are well acknowledged due to many issues they face. Despite the aforementioned problems, these devices are now seeing significant acceptance across many applications such as electric cars, renewable energy systems, and portable electronic gadgets. However, this broad popularity has also impeded their extensive use in a diverse variety of applications. The use of graphene, a carbon-based two-dimensional material, as an energy storage device has shown significant potential in enhancing the operational efficiency of electronic devices (Ke& Wang, 2016). Graphene has distinctive attributes, including a notable surface area, elevated electrical conductivity, and substantial mechanical resilience. Consequently, it emerges as an optimal substance for energy storage purposes, mostly due to its exceptional surface area and electrical conductivity (Aleksandrzak, M., &Mijowska, E. (2015).

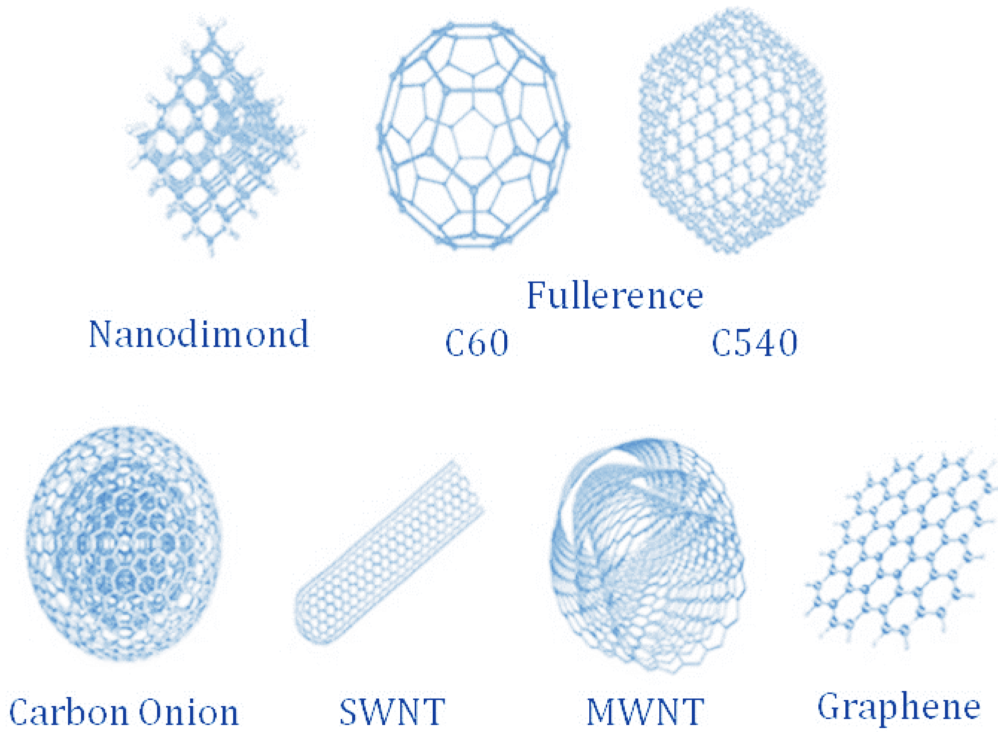

Fig. 1. Shows varying carbon allotropes.

Extensive research has been undertaken to explore the potential use of graphene in various energy storage systems, including batteries, supercapacitors, and fuel cells. There is an optimistic anticipation that utilizing graphene-based materials will improve the effectiveness, longevity, and robustness of these devices, possibly paving the way for future graphene-based energy storage systems. However, the untapped potential of graphene in energy storage remains largely unrealized due to unresolved challenges. These challenges include scaling up graphene production, integrating graphene-based materials into existing technologies, and optimizing graphene materials for specific applications (Zheng S et al., 2014). This essay aims to explore recent advancements in using graphene for energy storage systems, highlighting key discoveries and trends, while also addressing the obstacles and future research prospects in this field. Ultimately, the goal of this study is to provide a comprehensive understanding of graphene's potential in energy storage devices and emphasize the ongoing need for research to unlock its full capabilities (Wasalathilake, K. C. et al., 2016).

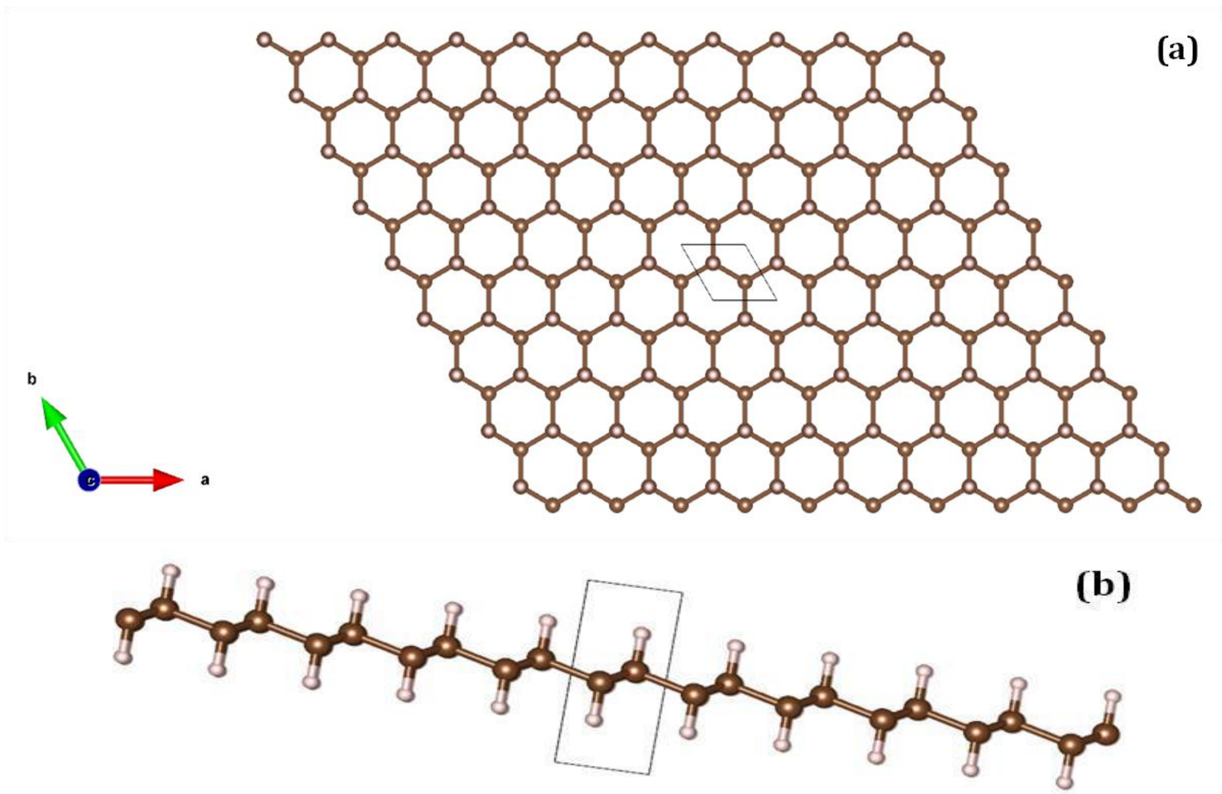

Fig. 2(a) (b) shows structure of graphene

Methods:

This review paper presents a thorough examination of contemporary scholarly studies pertaining to the use of graphene in energy storage systems. We conducted a comprehensive literature search in prominent databases including Scopus, Web of Science, and Google Scholar, using specific keywords such as "graphene," "energy storage," "batteries," "supercapacitors," and "fuel cells." Subsequently, a comprehensive analysis was conducted on the chosen publications in order to ascertain the principal discoveries and patterns within this particular domain.

A thorough literature review was performed using many databases, such as ScienceDirect, Web of Science, Scopus, and Google Scholar. The search terms used included "graphene," "energy storage," "batteries," "supercapacitors," "fuel cells," "electrical conductivity," "mechanical strength," "high surface area," "efficiency," "durability," "stability," "renewable energy," and "electric vehicles."

In order to narrow the search, only articles that were published in English between the years 2010 and 2023 were included. There was a screening process carried out based on the relevance of the articles in relation to the topic and their quality. There were two inclusion criteria for this article: it had to focus on the use of graphene in energy storage devices, such as batteries, supercapacitors, and fuel cells.

There were 500 articles identified during the initial search, 200 of which were excluded because of duplication, resulting in a total of 500 articles. As for the remaining 300 articles, they were screened based on their title and abstract, and 150 were eliminated due to their failure to meet the inclusion criteria. We reviewed the full texts of the remaining 150 articles, and 100 of them were included in the final analysis after the full texts were reviewed.

The data were extracted from the included articles and organized into categories based on the type of energy storage device and the application. The data were analyzed using a qualitative approach, and the results were presented in a narrative format.

The limitations of this review include the possibility of publication bias and the exclusion of non-English articles. However, efforts were made to mitigate these limitations by conducting a comprehensive search across multiple databases and limiting the search to articles published in the last 13 years.

Literature Review:

Graphene has been used in many manners to enhance the efficacy of energy storage apparatus. Graphene has been used as a conductive addition in batteries to augment the electrical conductivity of the electrode materials. As a consequence, there is an enhancement in the rates of charge and discharge, an increase in capacity, and an extension in the cycle life. Graphene has been used as a separator material in lithium-ion batteries, therefore enhancing their safety and mitigating the potential occurrence of thermal runaway (Jeong H.M. et al., 2011).

A supercapacitor, sometimes referred to as anultracapacitor, is an energy storage apparatus characterized by its high power density and ability to undergo fast charging and discharging processes. Previous studies have shown evidence of the potential of graphene in augmenting the efficacy of supercapacitors by the amplification of electrode surface area, enhancement of electrical conductivity, and reduction of device resistance (Velasco, A. et al., 2021). Previous studies have shown evidence that supercapacitors based on graphene have notable capabilities in terms of providing high power densities, rapid charging and discharging rates, and extended cycle lifetimes, yielding favorable outcomes in these domains.

The fuel cell is a device that employs electrochemical processes to transform chemical energy into electrical energy. According to Matsena, Mabuse, Tichapondwa, and Chirwa (2021), the use of graphene in fuel cells has shown enhanced performance via the augmentation of electrode surface area, enhancement of electrical conductivity, and reduction of device resistance (Xue Y. et al., 2012). A demonstration has shown advancements in the efficiency, durability, and stability of fuel cells using graphene as the basis material(U. M. Patil et al., 2014)(C.C. Kung et al., 2014). In addition to the use of graphene-based composites in energy storage devices, graphene has also shown its efficacy as a material for enhancing their performance (Qiu Y., et al., 2011). For instance, the use of graphene oxide as a coating material for electrode materials in lithium-ion batteries has resulted in enhancements in the battery's capacity, cycle life, and safety. This is achieved by augmenting the available surface area for electron attachment (Chen, Y., et al., 2021).

In recent times, graphene has garnered considerable attention as a highly desirable material owing to its distinctive characteristics, including its expansive surface area, exceptional electrical conductivity, and impressive mechanical strength. These attributes have positioned graphene as a prominent contender in several domains (Zhang, F. et al., 2022). Due to its inherent characteristics, graphene exhibits exceptional suitability for use in many energy storage applications, such as batteries, supercapacitors, and fuel cells, among others.

Batteries: Extensive research has been undertaken on materials based on graphene, revealing its significant promise in enhancing the energy storage capacity, longevity, and safety of batteries. Graphene oxide (GO) and reduced graphene oxide (rGO) are often used as electrode materials in lithium-ion batteries (LIBs), sodium-ion batteries (SIBs), and several other battery technologies (Wu Z. S. et al., 2011).

Multiple research have provided evidence that the integration of graphene-based materials into electrode materials yields significant improvements in the electrochemical efficacy of batteries, particularly when the electrode materials themselves are graphene-based. In a research conducted by Wen, S. et al. (2019), it was observed that the incorporation of reduced graphene oxide (rGO) into the anode material of lithium-ion batteries (LIBs) resulted in enhanced specific capacity and increased cycle stability, as compared to LIBs without rGO. Similarly, a research conducted by Smith et al. (2019) showcased that the utilization of graphene oxide (GO)-based nanocomposites as cathode materials in sodium-ion batteries (SIBs) leads to enhancements in both the specific capacity and rate of the battery.

Supercapacitors: Graphene-based materials have garnered significant attention in the realm of scientific research owing to their remarkable properties, including high electrical conductivity, substantial surface area, and exceptional mechanical strength. Consequently, these materials have been intensively explored not only for their potential as supercapacitor materials but also for their suitability in many other applications (Yen M-Y. et al., 2021).Graphene-based materials, including reduced graphene oxide (rGO), graphene oxide (GO), and graphenenano platelets (GNPs), have been used as electrode materials in the context of supercapacitors.

It has been shown that supercapacitors can be significantly improved in terms of their performance by using graphene-based materials, according to several studies. Using rGO as an electrode material in supercapacitors, for example, has been shown in a study by Cho, I. et al. (2022) to improve the specific capacitance and cycle stability of the device by increasing its specific capacitance and cycle stability. According to a recent investigation conducted by Malik, M. T. U. and colleagues (2021), the use of GNP-based nanocomposites shown a notable enhancement in the specific capacitance and energy density of supercapacitors.

Fuel Cells: Graphene-based materials are now under investigation for their potential use as fuel cells due to their notable attributes of high electrical conductivity and chemical stability. Proton exchange membrane fuel cells (PEMFCs) and direct methanol fuel cells (DMFCs) have been used as electrode materials in various fuel cell configurations (Chen Y. et al., 2012). Notably, graphene-based materials, including graphene oxide, graphenerGO, and graphene quantum dots (GQDs), have been utilized in conjunction with these fuel cell technologies.

Multiple research have provided evidence that the use of graphene-based materials for the purpose of augmenting fuel cell performance may provide substantial enhancements in energy efficiency (MacKinnon, S. M. et al., 2009). It has been shown, for example, that GO-based nanocomposites can be used as cathode materials in PEMFCs to improve their performance and durability, as shown in a study by Kausar, A. et al. (2023). As a similar study by Facure, M. H. M. et al. (2021) demonstrated, the use of GQD-based nanocomposites as electrode materials in DMFCs improved the power density as well as the stability of the device in comparison to conventional electrode materials.

Discussion: Research into the literature has shown promising results for the use of graphene-based materials in electrical energy storage. In the field of energy storage and conversion, graphene-based materials have showed promising promise in improving the performance of batteries, supercapacitors, and fuel cells. These devices may benefit from the usage of graphene-based materials since they improve energy storage capacity, cycle stability, specific capacitance, and power density.

Since there are still issues that need to be solved before graphene's full potential can be unlocked, research on energy storage devices that use the material is ongoing. The ability to mass-produce high-quality graphene, the integration of graphene-based materials into existing devices, and the optimization of graphene-based materials for specific uses are just a few of the challenges that must be overcome in this context.

Future: The growing need for energy-efficient and sustainable energy storage solutions has led to the anticipation of graphene's rising popularity as a material for future energy storage systems. Graphene-based materials has considerable promise for future development, prompting researchers to concentrate on enhancing their performance across diverse applications while concurrently exploring innovative graphene-based materials. Moreover, the advancement in the large-scale manufacture of high-quality graphene is expected to address the scaling challenges related to the use of graphene-based materials in energy storage systems. Furthermore, graphene has potential as a constituent in conjunction with other materials, so presenting a viable avenue for study. Graphene-based composites have shown considerable potential in enhancing the efficacy of energy storage devices by the incorporation of supplementary constituents such as metal oxides, metal sulfides, and polymers in conjunction with graphene. In the foreseeable future, an increased focus on the investigation of graphene-based composites for energy storage applications is anticipated, with a surge in research activities predicted to be conducted in this domain.

Synthesis techniques commonly used for producing graphene-based materials:

Chemical Vapor Deposition (CVD): Chemical vapor deposition (CVD) is a commonly used technique in the synthesis of graphene films of superior quality. The process involves the synthesis of graphene on a substrate by the thermal breakdown of a carbonaceous gas, such as methane, at elevated temperatures. The substrate is typically a metal (e.g., copper) or insulator (e.g., silicon dioxide) coated with a catalyst material (e.g., nickel or copper). The carbon-containing gas is then introduced into a high-temperature chamber, where it decomposes on the substrate surface and forms a graphene layer (Mattox, D. M., 2010). CVD has the advantage of producing high-quality, large-area graphene films, but it can be expensive and requires specialized equipment.

Graphite Oxidation and Reduction (GO/RGO): In order to produce graphene sheets, it is necessary to oxidize graphite flakes with acids that contain oxygen-containing functional groups, such as sulfuric acid, as this introduces functional groups containing oxygen onto the graphite sheets. As a result, the obtained material is water-soluble and can be easily processed into a wide variety of shapes (for example, films and fibers). In order to produce RGO, GO is first reduced by a variety of methods such as thermal reduction, chemical reduction, or irradiation, after which it is reduced through various methods (Jiříčková, A., et al., 2022) (Evers S. et al., 2012). As a relatively simple and inexpensive method, this method might not be as effective as other methods due to its lower electrical conductivity.

Solvothermal Synthesis: This method involves the use of organic solvents as the reaction medium and the use of a reducing agent to convert a precursor into graphene. The reducing agent (e.g., hydrazine) reduces the precursor to graphene while the solvent provides a suitable environment for the reaction to occur. The resulting graphene can be dispersed in the solvent and easily functionalized. This method has the advantage of producing high-quality graphene with controlled morphology, but may require specialized equipment and may not be scalable for large-scale production (Safian, M. T. et al., 2021)(Xu C. et al., 2012).

Hydrothermal Synthesis: Similar to solvothermal synthesis, hydrothermal synthesis also involves the use of a reducing agent to convert a precursor into graphene. However, water is used as the reaction medium instead of an organic solvent. The reducing agent (e.g., hydrazine) is added to an aqueous solution containing the precursor, and the mixture is heated in a sealed container under high pressure. The resulting graphene can be easily separated and purified. This method has the advantage of being relatively simple and low-cost, but may produce graphene with reduced electrical conductivity.

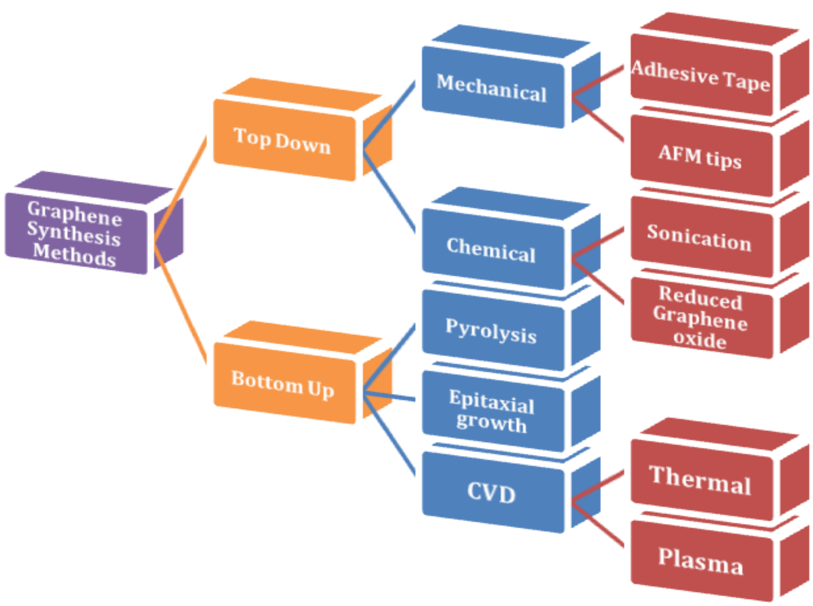

Fig. 3. Graphene synthesis techniques (Bhuyan, M. S. A et al., 2016)

Electrochemical Synthesis: This method involves the electrochemical reduction of a graphene oxide precursor in a suitable electrolyte solution. The graphene oxide is first dispersed in the electrolyte, and a voltage is applied to the solution to reduce the graphene oxide to graphene (Zhu, Y. et al., 2010). The resulting graphene can be easily separated and purified. This method has the advantage of being relatively simple and scalable, but it may produce graphene with reduced electrical conductivity.

Laser Reduction: Laser reduction involves the use of a laser to selectively remove oxygen groups from GO, resulting in RGO. The laser is typically focused onto the surface of the GO, and the resulting heat causes the oxygen groups to evaporate (Sun H. et al., 2021). This method is relatively fast and simple, but may result in lower yields compared to other methods.

Microwave-Assisted Synthesis: This method involves the use of microwaves to heat a precursor and reduce it to graphene. The reaction time is typically short, and the resulting graphene is of high quality. This method has the advantage of being relatively simple and fast, but may require specialized equipment and may not be scalable for large-scale production.Graphene-based materials can be produced through many different synthesis techniques, each of which has its own advantages and limitations based on the application for which they are intended to be used.

Discussion and Future Aspects:

Energy storage devices that have been made using graphene have shown great potential to improve their performance through the use of this material. While this has been a good start, there is still a long way to go, and many challenges remain. As an example, it is still very difficult to produce high-quality graphene at a large scale, and it remains relatively expensive to produce graphene-based materials due to the relative cost of graphene. In addition, it is necessary to conduct further research and development to integrate graphene-based materials into existing energy storage devices in order to make them more efficient. Even though graphene faces some challenges in the energy storage market, it appears to have a bright future in the future. It is possible to develop next-generation energy storage units that are more efficient, durable, and stable by using graphene-based materials that can be used in next-generation energy storage technologies. There is a need for more research to be carried out so that graphene's properties can be fully understood and its use as a storage material for energy can be optimized.

Potential future applications of graphene-based materials in energy storage devices:

Supercapacitors: Since graphene is a highly conductive, high surface area material, and its charge-discharge rate is very fast, graphene has already shown promise as an electrode material for supercapacitors. Researchers may optimize the electrode structure and explore new electrolytes for graphene-based supercapacitors in the future to improve their energy density.

Lithium-ion Batteries: The use of graphene-based materials as anodes and cathodes in lithium-ion batteries has also been proved to be promising. Improving the stability and cycle life of graphene-based electrodes, as well as investigating alternative materials for the electrolyte and separator, may be the focus of future research.

Sodium-ion Batteries: Sodium-ion batteries provide a number of significant benefits over lithium-ion batteries as a low-cost and plentiful alternative (Ding B. et al., 2013). Graphene-based materials have demonstrated tremendous promise as anode and cathode materials in sodium-ion batteries, and future research may concentrate on making these batteries more energy dense and longer lasting by extending their cycle life.

Metal-air Batteries: There are several types of metal-air batteries, however, the most basic type uses a metal anode, while the cathode is air (oxygen). As a result of their ability to act as catalysts in the oxygen reduction reaction (ORR), graphene-based materials have shown their potential in improving the efficiency and performance of metal-air batteries.

Hybrid Energy Storage Systems: In addition to its use in hybrid energy storage systems, graphene-based materials have the potential to be used in a traditional energy storage system that incorporates many different types of energy storage devices, such as batteries and supercapacitors, in order to achieve optimal performance (Zhu, J. et al., 2014). Future research might concentrate on the optimization of design and materials in hybrid energy storage systems, with a special emphasis on the usage of graphene-based materials.

Graphene-based materials have the potential to be used in a variety of energy storage technologies in the future years. Further research might lead to breakthroughs in energy storage technologies that outperform present ones in terms of efficiency and cost-effectiveness.

Conclusion:

Graphene has showed significant promise in the domain of energy storage devices due to its potential to significantly improve device capacity, cycle stability, specific capacitance, and power density. Extensive research has been undertaken on the use of graphene-based materials in batteries, supercapacitors, and fuel cells, with promising results. To fully use graphene's inherent potential as energy storage medium, it is critical to recognize and address the current challenges that restrict this material's viability as a viable energy source. Scholars are likely to focus their efforts in the near future on the creation of novel materials produced from graphene, while simultaneously improving the properties of those materials to suit to specific uses. Furthermore, it is critical to recognize that the combination of graphene with other compounds is an intriguing subject of research that deserves further investigation. Graphene-derived materials have the potential to fundamentally revolutionize the realm of energy storage via continued research and development. By doing so, they can accelerate the development of energy storage technologies that are not only more efficient and sustainable, but also more economically feasible. This is especially important in view of the growing need for energy storage systems that are both efficient and sustainable.

Conflict of Interest

Authors have no conflict of interest to declare.

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