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Graphene for Supercapacitors and Energy Storage

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ABSTRACT

The growing global need in viable and effective energy storage means created higher interest in the use of supercapacitors since they exhibit their high ability in power density production, fast charge/discharge rates, and extended cycle lives. This chapter discusses some of the basic principles of operation of supercapacitors especially the difference between electric double-layer capacitors (EDLCs) and pseudocapacitors. The main parameters of the performance are given as important parameters of assessing devices efficiency: specific capacitance, energy density, power density, and cycling stability. The extraordinary electrical conductivity material, large surface area with mechanical strength and chemical stability has triggered the use of graphene in the invention of the next generation of supercapacitor electrodes. The chapter takes a closer look at the electrochemical applications of graphene and expounds on the range of manufacturing pathways, mentioning chemical vapor deposition (CVD), the enhanced Hummers process and liquid phase exfoliation to mention just a few. The focus is given to the creation of graphene whereas it is combined with carbon nanotubes (CNTs), metal oxides (MnO_2, RuO_2), and conducting polymers (e.g., polyaniline, PEDOT) to improve charge storage phenomena. Various arrangements of supercapacitor devices are also discussed and the comparison of symmetric and asymmetric structures, solid-state and bendable ones are discussed. Such formats play a pivotal role in aligning the supercapacitors to any domains of application. Lastly, the chapter points out practical implementation of graphene supercapacitors, not only in portable and wearable electronics as well as grid-scale systems that will store energy. A promising direction is a hybrid supercapacitor battery system and high-performance energy systems in automotive and aerospace. Supercapacitors have the potential to become the fabric of energy technology in the future, especially in context of the desired properties as enabled by the fundamental characteristics of graphene, and by taming other functional device structures.

Keywords: Graphene-Based Nanomaterials; Graphene Supercapacitors; Electric Double-Layer Capacitor; Energy Density; Composite Electrodes; Flexible Energy Storage; Hybrid Energy Systems; Wearable Electronics; Aviation Electronics.

INTRODUCTION

The EDLCs mainly work through the electrostatic formation of an electric double layer at the interface between an electrode and an electrolyte. The principle of this method is the charge and discharge of ions on the surfaces of high-nucleation powders mostly, of carbon-based electrodes, which give large energy storage potential. The surface area, pore structure and the electrode material distribution will play the most critical role in determining the efficiency of EDLCs in energy transfer, which is highly influential to the capacitance and performance of the EDLCs.[1,2] The energy that is stored by pseudocapacitors is due to a process known as faradaic reactions which are electrochemical oxidation and reduction reaction on the surface of an electrode. Pseudo-capacitors can eventually exceed energy energy one of EDLCs due to

coincident redox responses that aid charge move and storage.[3,4,5] The advantage of pseudo-capacitors is their high level of specific capacitance and energy density but with concerns such as low conductivity and poor long-term cycle stability when compared to EDLCs.[6,7] The flexibility in the type of materials to use in building electrodes (pseudo-capacitors) like conductive polymer and transition metal oxide means that it is possible to develop structures that facilitate specific use.[8,9] The aspects of the material science concerning the electrodes have the significant effect on the capacitance and performance of these supercapacitors. The latest developments call attention to the idea of new materials, such as biomass-derived activated carbon, metal-organic frameworks, and carbon-based nanocomposites, explicitly constructed to improve the electrochemical properties of both EDLCs and PC systems. The innovations increase the conductivity and efficiency of operation in real-life conditions.[10] The main distinctions of EDLCs and pseudo-capacitors define whether they can appropriately be utilized in specific applications. EDLCs find most application areas needing high speed energy discharge, including power backup systems, and electric vehicles, due to their reliable energy discharge capacities and cycle stability. Oppositely, the pseudo-capacitors potential to deliver high energy density makes them ideal in systems requiring constant energy supply like electronic gadgets and renewable energy cycles.[11,12,13]

The methods that the Hummers 1 and 2 came up with have been revised to a more efficient and environmentally less intensive method to produce graphene oxide. The difference in the process of modified Hummers involves the alterations in the reagent concentration or usage of other types of oxidizing agents, which leads to safer waste disposal and higher yield.[14,15] Nomenclature Chemical vapour deposition (CVD) is considered a major technique in the preparation of graphene especially in the formation of high-quality film. CVD entails heating or heating of gaseous chemically precursors, frequently hydrocarbons, onto a substrate where they break apart at high temperatures. With the help of the process, it is possible to obtain continuous graphene sheets, which makes it suitable in electronic devices that require homogeneity and scalability.[16]

Fundamentals of Supercapacitors

Electric Double-Layer Capacitors (EDLCs) vs Pseudo capacitors

Supercapacitors are of two distinct types including electric double-layer capacitors (EDLCs) and pseudo-capacitors (PCs). The two types of capacitors also incorporate different ways of storing charge thereby giving them the different performance properties and thus fit them to be used in different applications. Understanding the differences between the two is vital towards advancement of energy storage systems, particularly efficiency, longevity and environmental impacts. The two types of super capacitors exhibit the rapid capabilities of charging and discharging which is essential in situations involving the need to provide electric power immediately (table 1). The inherent architecture of EDLCs enables a swift response to input signals, whereas pseudo-capacitors can be used to reach a similar performance as well because of its electrochemical properties.[6]

Graphene oxide and gadolinium-doped CNTs exhibit high conductivity and electrochemical stability, making them essential functional materials in supercapacitors.[17,18] Their synthesis and structural analysis form the foundation for optimizing energy storage performance.[19] Particularly, the electrical behavior of GO/S structures and the photoconductivity of CNTs offer enhanced energy density for next-generation devices.[20,21]

Table 1. Comparative Overview of EDLCs, Pseudocapacitors, and Hybrid Supercapacitors

Parameter	EDLCs (Electric Double-Layer Capacitors)	Pseudocapacitors (PCs)	Hybrid Supercapacitors	References
Charge Storage Mechanism	Electrostatic adsorption at electrode–electrolyte interface	Faradaic redox reactions	Combination of EDLC and PC mechanisms	Madhushani et al.[5], Essa et al.[6]
Capacitance Origin	Non-Faradaic double-layer effect	Faradaic charge transfer	Mixed behavior	Bandara et al.[4]
Energy Density	Low (5–10 Wh/kg)	Medium (10–40 Wh/kg)	High (up to 50–80 Wh/kg)	Khokhar et al.[22]
Power Density	Very high (>10 kW/kg)	Medium–high	High (balances energy & power)	Bandara et al.[4]
Cycle Life	Excellent (>100 000 cycles)	Lower due to structural degradation	Improved cycle stability with material engineering	Essa et al.[6]
Response Time	Instantaneous (<1 s)	Slower due to redox processes	Fast, slightly slower than EDLCs	Madhushani et al.[5]
Typical Materials	Activated carbon, graphene	Metal oxides, conductive polymers	Carbon-metal oxide composites	Meghanathan et al.[23]
Applications	Power buffering, regenerative braking	Memory devices, biosensors	EVs, grid storage, hybrid devices	Bandara et al.[4], Dhapola et al.[24]
Environmental Impact	Low; uses carbon-based materials	Moderate; uses metal oxides (some toxic)	Varies depending on composition	Meghanathan et al.[23], Dhapola et al.[24]
Sustainability Focus	Bio-derived carbons, green synthesis	Eco-friendly redox materials	Focus on balancing performance with green design	Dhapola et al.[24]

Combination of two technologies, a hybrid of EDLC and pseudo-capacitive chemistry has emerged as promising way to maximize energy and power densities and to overcome the unique limitations of the two capacitor types. The hybrid supercapacitors also have a higher-power density that the electric double-layer capacitors (EDLCs) possess along with a higher energy density enjoyed by the pseudo-capacitors, which increases their performance indicators.[22] Also, both types of environmental impact are significant, as enhancing the sustainability of a supercapacitor-based technology aligns with the global efforts to reduce the effects of energy consumption and selection of environmentally friendly materials. As research is emphasized, the exploration of alternative and sustainable materials that have the least impact on the environment about performance are also noted.[23,24]

Development and improvement of electric double-layer capacitor and pseudo-capacitor have increasingly become an essential combination of technological, materials science and green concerns. Their unique charge storage characteristics influence their functioning specifics and inform the decisions regarding the application settings to many aspects, which is why the advancement in the field deserves the attention.

Performance Parameters: Capacitance, Energy Density, Power Density, Cycle Life

Supercapacitors which are recognized as investigated energy storage show excellent

performance parameters essential in a wide variety of fields such as electronics and electric cars. Among the key performance metrics are capacitance, energy density, power density and cycle life all of which are central to overall effectiveness of supercapacitors. It is vital to understand the presented factors and how they interrelate so as to maximize upon the supercapacitor technologies thus making possible their expansive application. Capacitance refers to ability of a supercapacitor to hold an electric charge. These are mainly the surface area of the electrode material, the nature of the electrolyte and the structure of the electrode. The capacitance of the supercapacitors is a multiple of that of the ordinary capacitors and that makes them efficient energy storage media with a fast charging and discharging capability (table 2).

Table 2. Performance Parameters of Supercapacitors

Parameter	Description	Typical Range	Influencing Factors	Comparison (EDLC vs. PC vs. Hybrid)
Capacitance (C)	Ability to store electrical charge per unit voltage (F/g)	100–1000 F/g	Electrode surface area, electrolyte accessibility, porosity	EDLCs: High due to double-layer effectPCs: Moderate, enhanced by redox activityHybrids: Optimized
Energy Density (E)	Energy stored per unit mass (Wh/kg)	5–80 Wh/kg	Capacitance, voltage window ($E = \frac{1}{2}CV^2$)	EDLCs: 5–10 Wh/kgPCs: 10–40 Wh/kgHybrids: 30–80 Wh/kg
Power Density (P)	Speed of energy delivery per unit mass (kW/kg)	1–20 kW/kg	Equivalent series resistance (ESR), charge transfer rate	EDLCs: Very high (>10 kW/kg) PCs: MediumHybrids: High
Cycle Life	Number of stable charge/discharge cycles before degradation	10 000–100 000+ cycles	Electrochemical stability, electrode material resilience	EDLCs: >100 000PCs: 1000–10 000Hybrids: 10 000–50 000 (with optimization)

Liu et al.[25] assert that the supercapacitors exhibit high capacitance values because their porous structures increase surface area and ways of storing charges, therefore, enabling them to have high electrical performance in comparison to capacitors and batteries. The electrode composition such as Carbon nanofibers and hybrid composites are important in improving capacitance. Gu et al.[26] discuss carbon nanofiber usage as a strong base to various electroactive products and show that new combinations of materials can make an overall capacitance increase. The cooperation of different materials increases charge storing processes, which are critical in achieving higher energy density and power density with maintaining cycle life. The amount of energy that a substance contains per unit mass, also known as energy density, is an important parameter that separates supercapacitors with batteries. Despite their high-power densities, supercapacitors have traditionally a lower energy density than batteries, which makes them inapplicable in energy-intensive processes. Wang et al.[27] noted that balancing the optimization of energy density and power density is one of the issues of supercapacitor development because there is a desire to obtain good results in both parameters. On the other hand, new candidates such as nitrogen-doped carbons have recorded promising performance with energy density of 20,7 Wh/kg and preserving power capacities.

Similarly, power density which is the rate of energy delivery over time is also a characteristic

feature of super capacitors. Supercapacitors are usually capable of rapid release of energy compared to batteries and lend themselves to applications that require rapid power surges, and are thus used in regenerative braking systems of electric automobiles. Anand et al.[28] draw upon the fact that supercapacitors have achieved exceptional power density, which renders the device the ability to deliver a large instantaneous power drawing. GO and CNT-based materials demonstrate high specific capacitance (F/g), power density, and cycling stability.[29] Thermal analyses reveal that gadolinium-doped CNTs maintain structural stability up to 550 °C.[21] The EPR analysis of GO composites confirms the role of active surface centers in improving performance.[29]

Increased knowledge about cycle life proves that researchers have to conduct research on the electrolytes and materials that influence durability significantly. As an instance, supercapacitors with electrolytes that have optimized ionic conductivity or novel electrode materials that are pseudocapacitive might strongly enhance the cycle life of supercapacitors. Studies show that supercapacitors have the potential of 10 000 lifecycles with very good coulombic efficiency which implies that they are very stable/durable in the field.[30]

However, trade-offs between these factors are very important to consider. Zhao et al.[31] elaborate that with augmented energy density, a power performance trade-off is frequently met, where scholars suggest that the combination of both batteries and supercapacitor features is hybrid meant to mitigate these drawbacks. At that, the active combination of elements that offer the enhanced energy and power density enabling the retained extraordinary cycle life is the benchmark of the contemporary limitation of the supercapacitor study (figure 1).

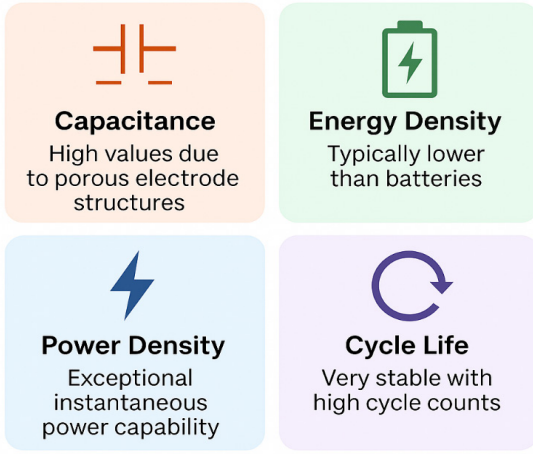

Figure 1. Performance metric of supercapacitors

The analysis of the supercapacitor performance shown the multifactor connection existing between the capacitance, energy density, power density, and cycle life. The evolutionary activities in the field of materials sciences along with the groundbreaking design of electrode and electrolyte will further advance the performance of supercapacitor to the utmost. The search of a perfect balance of these performance aspects is an important mission that is going to define the future of energy storage technology.

Graphene Properties Relevant to Energy Storage

A one-layer carbon atom structure arranged in a pattern called hexagonal lattice called

graphene has been an important substance in energy storage, notably in super capacitor and battery appliances. The great properties, in particular, high electrical conductivity, large specific surface area, and mechanical strength, make it an interesting choice to enhance energy storage systems (table 3). Graphene oxide offers a large specific surface area and oxygen-containing groups, enabling effective ion interactions in energy storage systems.[32,33] Sulfur-doped GO demonstrates thermal stability and negative thermal expansion, which are beneficial for high-performance supercapacitors.[34] The optical and electrical properties of GO/S structures make them viable for advanced nanoenergy platforms.[32] Graphene material is associated with significant increases in power and energy levels and, therefore, is essential to the development of future energy storage.[35] Due to its large surface area that can reach a maximum of 2675 m^2/g, graphene has a direct influence on capacitance behavior in supercapacitors (figure 2).

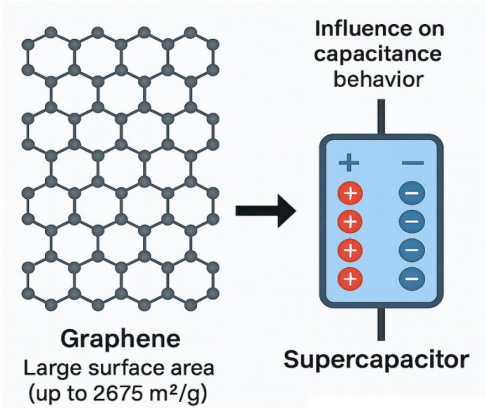

Figure 2. Graphene-Induced Capacitance Enhancement in Supercapacitors via High Surface Area Interface

This increases storage capacity of the charges necessary in the efficient operation of energy storage devices. Additionally, the high electrical conductivity of graphene leads to energy loss reduction during charge and discharge cycles, therefore, enhancing supercapacitor devices general performance.[36] Studies have revealed that supercapacitors made of graphene have the potential to store up to 100 to 500 F/g which is significantly higher when compared with the standard capacitor.[37] Despite the positive features, its scientists are faced with challenges, such as the tendency of graphene sheets to get back together during processing, effectively reducing the convenient surface area upon which charges could be stored. The stacking will minimize ion mobility therefore compromising performance. Some of the strategies to tackle these challenges involve development of composite materials which combine the graphene with other elements such as metal oxides and conductive polymers hence improving capacitance and stability. The synergistic properties of the building materials may be employed in the composite designs, therefore, bolstering the overall performance compared to the performance of the single material.[38]

In addition, environmental sustainability is also emerging as a deciding element in energy storage technologies. Graphene can be produced using various waste materials such as biomass, industrial wastes, which makes it less harmful to the environment caused by manufactured graphitic products. Such factor is not only supporting the idea of sustainable approach to the production of materials but also introduces a possibility of cost-effective means of production, which can potentially increase the usage of supercapacitors in the market.[39] Most remarkably,

three-dimensional (3D) graphene structures have proposed to find means of optimizing surface area and reducing restacking effects. The three-dimensional structures overcome the limitations of the two-dimensional graphene sheet and provide an enhanced accessibility of the ions and enhanced electrochemical performance in the supercapacitor devices.[40] Research indicates that the new topologies can be effectively utilized to increase the efficiency and capacitance value of supercapacitors, especially that of graphene supercapacitors by optimizing the pathways between charges and ions.[41]

Table 3. Key Properties of Graphene for Energy Storage Applications

Feature/Aspect	Description	Reference
Atomic Structure	One-layer carbon atoms arranged in hexagonal lattice; 2D structure	Papadiamantis et al.[35]
Surface Area	Up to 2675 m^2/g; enhances charge storage capacity	Lu et al.[36]
Electrical Conductivity	High conductivity allows faster charge/discharge cycles, reducing energy loss	Lu et al.[36]
Capacitance Range	Graphene-based supercapacitors can reach 100–500 F/g, far exceeding traditional capacitors	Salehfar et al.[37]
Mechanical Strength	High tensile strength adds structural stability during electrochemical cycling	Papadiamantis et al.[35]
Challenge: Restacking	Graphene sheets tend to agglomerate, reducing surface area and ion mobility	Obodo et al.[38]
Solution: Composites	Combining graphene with metal oxides or conductive polymers improves stability, capacitance, and ion transport	Obodo et al.[38]
Sustainability	Graphene production from biomass/waste materials provides a green, cost-effective alternative	Manik et al.[39]
3D Graphene Structures	3D architectures reduce restacking, enhance ion accessibility, and improve electrochemical performance	Qi et al.[40]
Pathway Optimization	Advanced topologies optimize charge/ion transport routes in supercapacitors	Zhang et al.[41]

Conclusively, graphene application in energy storage devices, particularly supercapacitors, is a multimodal approach that uses materials science, nanotechnology and environmental factors to offer new solutions to energy needs in future. Scientists are exploring numerous characteristics and future applications of graphene, which means that this outstanding substance is essential in terms of efficiency and sustainability of energy storage systems.

Fabrication of Graphene-Based Supercapacitor Electrodes

Graphene Synthesis: CVD, Hummers Method, Liquid Phase Exfoliation

Graphene a single -atom-thick sheet of carbon arranged in a hexagonal geometry has gained much attention due to its unique mechanical, electrical and thermal properties. Graphene needs synthesis in order to be integrated with numerous solutions in energy storage, electronics and composite materials. Many methods of producing a graphene are known with the most prominent among them being the chemical vapour deposition (CVD), Hummer's technique and liquid phase exfoliation. All processes possess unparalleled advantages and issues which

influence the quality, scale ability and utility of the synthesized graphene (figure 3).

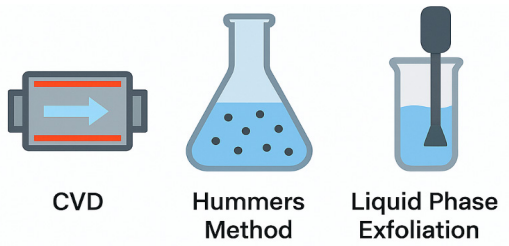

Figure 3. Their synthesis methods of graphene oxide

One of the commonly applied procedures in the synthesis of graphene oxide (GO) among the hummers is the graphite. The method based on the oxidation of graphite flakes through a mixture of concentrated sulphuric acid, potassium permanganate, and other oxidizing reagents with subsequent functionalization of the graphene sheets with oxygen groups.[42,43] An even smaller quantity of graphene oxide supposedly leads to the formation of reduced graphene oxide (rGO), which retains certain extent of oxygen content that influences eventual properties and applications.[43,44,45] It is necessary to control the temperature, and reaction time to adjust the degree of oxidation that is vital to achieving the desirable levels of oxidation and functionality in the final graphene oxide.[46,47] New technology in modified Hummers and new graphene manufacturing methods are being considered in terms of their economic and environmental health costs to promote sustainability in the environment.[48,49] The changes are directed towards reducing the number of toxic by-products associated with the traditional practices. Although other techniques (such as incorporating environmentally friendly solvent mixtures and organisms in the synthesis of graphene) have been proposed, the process suggested by Hummers will remain relevant due to its ease of access and the established procedure in the community of scientists.[50,51] GO was synthesized via a modified Hummers method, and its structure was characterized using Raman, XRD, and SEM techniques.[44] CNTs synthesized via arc discharge and CVD methods displayed high crystallinity confirmed through phase analysis.[52] GO–CNT hybrid electrodes demonstrated homogeneous dispersion and excellent electron transfer, resulting in improved performance.[53]

Graphene manufacturing processes like Hummers, CVD and the liquid phase exfoliation processes have enabled developments in the studies of materials. There is a unique advantage and limitation to each of these methods and it influences the choice of process based on the desired features of the product. Future actions can be devoted to optimization of these methods to the issues of scale, environmental sustainability of manufacturing process, and maintenance of high-performance characteristics which comply with planned uses of graphene in various spheres.

Composite Materials: Graphene with CNTs, Metal Oxides, Conducting Polymers

Graphene, carbon nanotubes (CNTs), metal oxides, and conducting polymers are some of their properties and applications that have attracted the serious investigation of composite materials in the last several years. Synergetic results in these composites enhance their mechanical strength, electrical conductivity, thermal stability and antimicrobial properties. Due to striking strength and electrical conductivity, graphene and carbon nanotubes are critical constituents of various composite systems. The addition of graphene oxide to polymer composite improves mechanical and barrier properties significantly, which is needed in the protective coatings and in corrosion resistance.[54] GO synthesized by the Hummers method yielded stable dispersions

after purification and reoxidation processes.[44] CNTs produced via CVD exhibited tunable conductivity when doped with gadolinium.[21,55] The electrical modeling of GO/S nanostructures was employed to predict device behavior.[44]

Metal oxides play key roles in composites composed of conductive polymers and those containing carbon-based materials. The binary metallic sulfide-based nanocomposites have also contained ZnO that serves twice, both in energy storage and sensing functions. Furthermore, metal oxides in mixtures with CNTs and graphene enhance the electrical conductivity and electrochemical properties of a composite that is going to be applied in supercapacitors and batteries. Study indicates that the mercy of electrodes in supercapacitors could be significantly reduced by using manganese in combination with graphene. Addition of conducting polymers such as poly aniline with graphene and carbon nanotubes improves the capabilities of charge transport which is critical in several sensor application areas. The improvement is attributed to the continuous pathways formulated by the networks of conjugated polymers that facilitate rapid transfer of the electrons, thus, increasing the sensitivity and effectiveness of the sensors used in glucose and another biomolecule detection.[56,57] GO and CNT-based nanocomposites were enhanced with metal oxides (e.g., ZnSe, MnO_2) and conducting polymers to boost electrochemical activity.[58] The photoconductivity of Gd-doped CNTs and thermal stability of GO/S composites highlight their multifunctional potential.[21] Surface properties were validated using XPS, EPR, and FTIR techniques. The properties of polymer-based composites with graphene and carbon nanotubes are under exploration in solving electromagnetic interference shielding, thermal management and flame retardancy. The strategic application of graphitic materials has been recorded by researchers to have a better thermal property that is desired in aerospace, automotive and electronic applications.[58,59] Carbon nanotubes (CNTs) increase thermal properties by raising a thermo-conductivity and mechanical strength when properly positioned in a polymer matrix (table 4).[17,18,21,60]

Table 4. Functional Roles and Synergetic Effects of Graphene, CNTs, Metal, Metal Oxides, and Conducting Polymers in Composite Materials

Component	Functional Role in Composites	Enhanced Properties	Application Areas	References
Graphene	Filler material; provides high mechanical strength and electrical conductivity	Mechanical reinforcement, corrosion resistance, barrier properties	Protective coatings, corrosion resistance, electronics	Arnal et al.[54]
Carbon Nanotubes (CNTs)	Structural and conductive framework in composites	Thermo-conductivity, mechanical strength, EMI shielding, electron mobility	Aerospace, automotive, sensor technology, electronics	Abaszade et al.[18,21] Zhang et al.[60] Chowdhury et al.[59]
Metal and Metal Oxides (e.g., Gd, ZnO, MnO_2)	Electrochemical activators and charge storage enhancers, used in nanocomposite formation	Improved electrochemical behavior, enhanced conductivity, dual role in energy/sensing	Supercapacitors, batteries, sensors	Abaszade et al.[17], Yasmeen et al.[56] Le et al.[57]

Conducting Polymers (e.g., Polyaniline)	Provide continuous charge transport pathways and enhance surface interaction with analytes	High electrical conductivity, sensor sensitivity, rapid electron transport	Biosensors (e.g., glucose sensors), flexible electronics	Yasmeen et al.[56]
Graphene + CNTs	Hybrid reinforcement agent with excellent interconnectivity	Increased mechanical strength, thermal conductivity, EMI shielding	Flame retardants, structural electronics, smart coatings	Zhang et al.[60]
Graphene + Metal Oxides	Charge storage and surface modification synergy	High capacitance, low internal resistance, long cycling life	Energy storage (supercapacitors, Li-ion batteries)	Yasmeen et al.[56], Le et al.[57]
CNTs + Conducting Polymers	Conductive matrix with tubular electron transport channels	Enhanced electron flow, improved mechanical flexibility	Biosensors, electrochemical sensors	Yasmeen et al.[56]
Polymer-based Graphene/CNT Composites	Multifunctional composites for environmental and energy applications	EMI shielding, thermal management, flame retardancy	Aerospace, wearable electronics, environmental safety	Zhang et al.[60], Chowdhury et al.[59]

To conclude, a combination of graphene, carbon nanotubes, metal oxide, and conducting polymer represents a revolutionary step in the field of materials science that drives technological progress but also addresses sustainability challenges that mankind has to face. Further research and development in the area will reveal novel functions and this will permit new applications in energy, electronics, environmental remediation and biotechnology.

Devices of supercapacitors

Symmetric vs. Asymmetric Supercapacitors

It is necessary that supercapacitors as the critical components in energy storage nowadays can be generally divided into two fundamental types, symmetric supercapacitors (SSCs) and asymmetric supercapacitors (ASCs). The main contrast between these two topologies is a similarity or disparity of the material of used electrodes, which leads to different values of electrochemical performance parameters such as energy density, power density, cycle stability, and voltage restriction limits. Symmetric supercapacitors utilize identical electrode materials structural on each part, and the materials are regularly made of a carbon-based material or transition metal oxide, which provides a diminished operating voltage, normally constrained to about 1,2 V because of thermodynamic prerequisites of the material.[61] By contrast, asymmetric supercapacitors employ two different electrode materials which can include a pseudocapacitive materials and a double-layer capacitor material and can thus span a larger voltage range that can go up to about 2,0 V. Such increased voltage operation straight away leads to increased energy densities, possibly even higher than with symmetric supercapacitors, (figure 4).[62,63]

The asymmetric system incorporating MXene materials is potentially promising to significantly amplify the working potential scale and reach above-average energy densities compared to the symmetric ones.[62,63,64] GO and CNT-based electrodes have been successfully implemented in symmetric, asymmetric, solid-state, and flexible supercapacitor architectures.[53] The structural compatibility and electrical stability of GO/S nanocomposites contribute to reliable device performance.[44] These materials are especially promising for lightweight UAV platforms.[64]

There is significant difference in energy density in supercapacitors (SC) between asymmetric and symmetric SC due to underlying structural and material differences. Symmetric supercapacitors have nominal energy densities of 5-10 Wh/kg, compared to asymmetric devices with nominal energy densities of 30-60 Wh/kg and are therefore more suitable to high performance applications.[65] Since asymmetric design incorporates high-specific capacitance materials in the positive or negative electrodes, it also leads to the fact that the adaptability of designing performance to meet specific power and energy demands is improved.[66,67] Such flexibility is necessary in consumer electronics applications, up to electric cars where cost and performance is paramount.

Stability of the cycle is an important factor which makes a difference between symmetric and asymmetric supercapacitors. Research indicates that, SSCs can have improved cycle stability with greater capacity retention remaining more consistent over the multiple charge discharge cycles. As an example, SSCs can retain much of their original capacitance in approximately 92 percent of the cycle after 1000 cycles, whereas, in some cases, ASCs can observe a decrease in capacitance retention. Its reliability is attributed to the fact that this level of stress remains even, as faced by the electrodes in symmetrical systems, opposed to varying degrees of stress in non-symmetrical systems that can lead to material demineralization in the long term.[68,69]

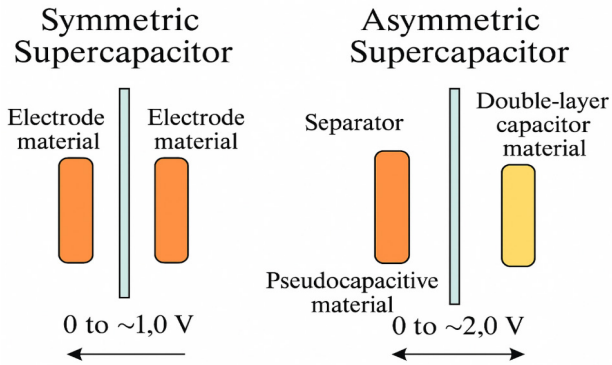

Figure 4. Symmetric vs. Asymmetric Supercapacitors

The extent of flexibility and adaptation of each type to some use situations is not only to emphasize their purpose but also on potentials of their performance in real circumstances. The progress of the supercapacitor lies in the enhancement of the performance of the supercapacitors through the innovation of new materials and design practices. To achieve green supercapacitors, researchers are examining the various viable biomaterials of constructing electrodes.[70] In symmetric designs, GO and CNTs are used as identical electrode materials for balanced performance, whereas in asymmetric models, voltage window and energy density are significantly improved.[17,44] Gd-doped CNTs used as anodes offer enhanced energy conversion capabilities.[21] Structural differences were revealed via EIS and Raman spectroscopy.

To conclude, comparative analysis of the symmetric and asymmetric supercapacitors distinguishes peculiar advantages and disadvantages defining their definite application in the aspect of the energy storage technology. SSCs are more stable in the number of cycles and easier to manufacture, whereas ASCs are more flexible in application terms of energy density and operating range, always being boosted by research and continuous innovation into the material and design of these types of batteries. With the rise in demand of complex energy storage solutions, it will be important to understand these differences that would help in maximizing

the use of supercapacitor in various sectors.

Solid-State and Flexible Supercapacitor Designs

GO and CNT-based solid and flexible electrodes maintain performance under vibration and mechanical stress.[71] The photoelectric properties of GO/S composites offer multifunctionality in smart wearable and flexible electronics.[22] These systems are highly applicable to emerging flexible technologies.[72,73,74,75] The trend toward solid-state and flexible supercapacitors technologies is an important response to the growing world energy demand, the demand of sustainable development and energy storage needs. The supercapacitors have grown in popularity because of the high-power density, high speed of charging and discharging and long-life cycle (table 5). These properties make them suitable in mobile equipment's, electric vehicles and green energy devices.[76,77] The newest trends concern the integration of such materials as MXenes, nanomaterials, and biomass-derived composites of carbon, enhancing performance and facilitating environmentally friendly production technologies.[78,79]

Table 5. Comparison of Supercapacitor Architectures: Design, Electrolyte, Electrode Materials, and Mechanical Flexibility

Design Type	Electrolyte Type	Electrode Materials	Mechanical Flexibility	Energy Density
Solid-State SC	Solid Polymer Electrolyte (e.g., PVA/H_3PO_4, gel-based)	Graphene, CNTs, MnO_2, Polyaniline	Rigid or semi-flexible	Moderate–High (up to 20 Wh/kg)
Flexible SC	Gel or solid-state electrolyte	rGO, MXenes, Conductive Fabrics, Carbon textiles	High (bending, stretching)	Moderate (5–15 Wh/kg)
Quasi-Solid-State	Hybrid (liquid/solid gel systems)	Graphene composites, Metal oxides, Conducting polymers	Moderate–High	High (>20 Wh/kg)
Stretchable SC	Ionic gel electrolytes	Wrinkled graphene, kirigami-structured CNTs	Very High (stretch >100 %)	Low–Moderate (2–10 Wh/kg)
Printed SCs	Solid or gel electrolytes	Ink-form rGO, Carbon inks, AgNP composites	High	Low–Moderate

The other factor in the development of the supercapacitor technology is the optimization of the production process. New manufacturing techniques like 3D printing, new coating techniques allow fine tuning of material properties and structures in the development of super capacitors. In addition to enhancing the performance measures, these strategies lead to the scalability of production, and therefore, these technologies are more favorable to commercial purposes.[80,81] In the development of the next generation high-performance flexible supercapacitors, the integration of new production methods and new materials will play a definitive role. As sustainability changes the future of energy storage, researchers are looking at the lifetime and recycle of supercapacitors. By introducing the ideas of green chemistry in the development and fabrication of supercapacitors, reduction in environmental impact could contribute to the development and growth of renewable energy sources.[82,83] Such an all-round approach of energy storage efficiency and saving the environment aligns with the global endeavors of carbon neutrality and the fight against climate change.

An academic to industrial collaboration in future will play a critical role in translating research findings into commercially viable super capacitor technology. The continued development of

relevant legislations, standards and practices in the field of energy storage will equally influence the course of research and development initiatives in the same area. Adoption of frameworks that focus on innovation, efficiency, and sustainability can trigger a transition in energy storage and use in most applications. Optimization of the solid-state and flexible structure of the supercapacitors is not a simple process, and it consists of innovative material research, cutting-edge production technology, and a special emphasis on sustainability. The development of these aspects will help supercapacitor technology to fulfill growing demand of power with an active environmental context and promise reliability, efficiency and environmental friendliness in power storage applications.

Applications in Energy Systems

Portable and Wearable Electronics

Portable and wearable electronics is the sphere that has developed rapidly due to the improvements in materials and methods of energy storage, which have led to a reduction in the size and efficiency of gadgets and a greater level of versatility. These enhancements are critical to the invention of the lithium-ion batteries (LIBs) which have become the main mode of energy storage of handheld devices, electric vehicles, and more complex systems such as solar energy storage. The nature of LIBs in terms of chemical composition and design features defines its efficacy. Banerjee et al.[85] clarify the redox mechanisms and stability of the nickel-rich cathodes which are crucial to the success and stability of high-capacity lithium-ion batteries used in everything, including handheld devices and even electric vehicles. As the technology of these systems keeps improving, there is a lot of its wide application in the world of mobile electronic devices. This outdoor operation enhances the usefulness of wearable electronics a lot as it can continue its task undisturbed even without the conventional power. In addition, the unceasing advance development of energy storage devices like supercapacitors and similar composites bring great advantages in the management of power sources of portable devices. Investigation of Ravandran et al.[85] is devoted to supercapacitors based on tungsten dieseline, where the emphasis is on the further development of high-energy density storage devices that meet the fast and unpredictable power needs of modern portable devices.

Sustainable designs and the trend of green energy embraces thermoelectric and triboelectric nanogenerators (TENGs). These are technologies that can convert ambient energy into usable electricity required by self-powered devices. According to the study presented by Suneetha et al.[86], there are gains made in the field of triboelectric nanogenerators using electronic trash, which suggests that the given materials can contribute to a considerable increase in the energy harvesting capabilities of wearable devices. The technique can not only meet the demand in energy production but also increase sustainability efforts in the manufacturing of electronics.

Due to recent innovative storage solutions, the flammability of the lithium-ion battery electrolytes has indeed become a lesser cause of worry. Afif et al.[87] research the fluoride-doped solid electrolytes to minimize risks, enhance the ionic conductivity, and address the concerns about the safety of the standard lithium-ion batteries and the risks of their failure. It is expected of this study to come up with batteries that are exceeding the existing performance related with safety of the users in every application of the portable electronics.

Mass adoption of the integration of material science and energy storage technologies, coupled with electrical design, are changing the field of portable and wearable electronics tremendously. Further designing of modern gadgets is being transformed into well-developed technologies that employs LIBs, develop flexible materials and address various challenges such as EMI and thermal management to meet the existing user demands. Future research projects in various areas are

promising a brighter future of portable electronics which can enable imaginative applications that are deemed impossible up to now.

Grid-Level Energy Buffering

Grid-level energy buffering is a growing part of our present-day energy system, and its role is particularly relevant now due to the increasing usage of renewable sources of energy. Renewable energy generation is intermittent; therefore, the demand of secure, reliable power calls upon robust systems. The energy storage technologies play a pivotal role in dealing with the fluctuation in supply and demand. These solutions reduce the problems of finite supply of renewable resources and helps in enhancing grid reliability and interdependence on traditional fossil sources. Grid level energy buffering encompasses several approaches, both traditional e.g. pumped storage hydropower (PSH) and novel e.g. advanced battery technology. Today, pumped storage hydropower (PSH) remains one of the popular and effective means of large-scale energy storage that is characterized by a high capacity and cost-effectiveness.[88,89] Some shortcomings of pumped storage hydroelectricity (PSH) are spatial related, implying that alternatives, such as those based on lithium-ion battery and thus able to be deployed more versatilely, redox flow batteries (RFBs) are wanted. These technologies of batteries are delivering high energy density and equally exhibit high application flexibility in many uses such as industrial power control and electric vehicle integrations.[90,91] GO and CNT-based supercapacitors are ideal for grid-level peak shaving and fast energy buffering.[92] Their high cycling durability (>10^4 cycles) and power density make them promising battery alternatives. Their thermal management properties enable long-term operation in dynamic grid environments.[21]

The other important technology is interchangeable fuel cells and electrolysis in the production of hydrogen. These inventions give a mixed strategy of energy storage and distribution because they utilize water to produce hydrogen when there is excessive generation of renewable energy. Then this hydrogen could be reused again in fuel cells to generate power at the peak load and introduce sustainable power into grids and enhance stability. Their miniature and lightweight design also makes proton exchange membrane electrolysis very suitable to be coupled with renewable energy sources.[93] The integrated cooperation of a variety of energy technologies can possibly optimize the flexible operation of the dispersed energetic resources, such as the thermal generating and renewable sources. Using smart grid technologies improves the efficiency of resources and supports the idea of sustainability through interoperability.[94] Smart microgrids underline the opportunities of new energy management systems, which ensure the possibility to monitor and control the power supply of multiple disparate generating sources in real-time. Such flexibility is critical in balancing the fluctuating energy production of renewable sources and properly always fulfilling the needs of the consumer and in a cost-effective manner. The effort that will be taken now and into the future to enhance energy storage technology and the incorporation of those technologies into the grids will have an enormous influence on energy stability in the future and take us toward a more reliable and sustainable energy environment. Transformation into renewable energy necessitates a broader focus on energy storage, and at this point we should focus on groundbreaking technologies improving efficiency, effectiveness and environmental friendliness.[95]

The current tendency of the energy buffering mechanisms is burgeoning to indicate the necessity to incorporate diverse storage technologies into the energy systems to make them more resilient and benign. Our commitment to the solutions to the challenges of renewable energy integration can be illustrated by the current study of innovative materials and technologies including redox flow batteries, hydrogen solutions, and enhanced lithium-ion systems. Efficient

buffering of energy at the grid level is based on the ability to adapt, optimize, and innovate in different energy systems.

Hybrid Supercapacitor–Battery Systems

Hybrid supercapacitor-battery systems (HSBSs) is estimated to be a feasible approach to satisfy the growing demand of efficient energy storage solutions in variety of applications, including electric vehicles (EVs), portable electronics, and integration of renewable energy sources. Such systems take these unique benefits of the supercapacitors and the batteries and combine them together by using supercapacitor benefits of high-power density, fast charge-discharge rate, and cycle life, and the high energy density that the batteries have to offer. The resulting dual approach aims to counter the limitations of independent energy storage systems and provide better performance at energy, power and operating efficiency levels.[96,97]

Hybrid supercapacitors the electrochemical properties and structure of electrode materials are closely associated with the performance of hybrid supercapacitors. A study performed by Sivakumar et al.[98] underlines the significance of the electrode composition stating that battery-type electrodes may enhance specific capacity through efficient redox charge transfer thus, potentially increasing energy density. The economics of hybrid supercapacitors-battery systems are slowly becoming a major line of research inquiry. It is vital to evaluate the life-cycle cost of the two sectors as well as the consumers, and the return on investment is vital, as in the material science and technology, an invariable pricing cutdown along with the increased performance parameters is effective. The analysts expect that major increase in these systems deployment would be observed based on high efficiency and reduced environmental impact in comparison with traditional energy storage technologies.[99] It is projected that electric vehicles that would utilize hybrid systems would achieve lower fuel costs and indeed, greater fuel range because of the synergistic effects of their energy storage components.[100]

Hybrid systems Hybrid storage systems are a key to use renewable energy sources like wind, solar power more efficiently. Combining supercapacitors with the energy storage capacity in batteries would allow harnessing the energy generated in large volumes during times when energy is readily available and could deploy this energy quickly whenever the demand fluctuates. Research indicates that use of these systems increases flexibility of operation in microgrid structure and hybrid storage systems are important tools in ensuring that supply and demand are well balanced.[101,102]

Finally, the development of hybrid supercapacitor-battery systems is an indication of significant development in achieving more efficient, reliable and effective energy storage opportunities. Not only do these technologies reduce the pitfalls of the traditional battery and super capacitor alone, but they also utilize their synergistic changes to offer a stronger, versatile energy landscape. In the way the science goes, as exemplified by materials and design possibilities continuously increasing storage capacities, the future of how energy will be handled can be staring with the efficient use of hybrid energy production methods.

Automotive and Aerospace Applications

The world of automobiles and airlines is increasingly focusing on new materials to meet the demands of lightweight, high-strength parts, and at the same time increase safety and fuel consumption. Many have made a remarkable shift at using composite materials which has been shot up by their superior mechanical properties, corrosion resistance and versatile design that is very important in the two industries. Reinforced composites made of carbon fiber exhibit a better strength to weight preparation, and hence they can be used where weight is paramount

and therefore carbon fiber reinforced composites are more preferred in making aeroplane structures and automobile frame bodies.[103,104] Novel research concerning the hybrid composite such as carbon and bamboo fibre composites highlights the importance of vibration and acoustic characterization that are required industry applications in automotive and aerospace industry. The damping property of composite materials can play an important role in their performance under dynamic load conditions, as the vibration control of the structure is a paramount issue concerning the passengers and the soundness of the structures.[105] Focus on improving damping properties of materials is essential in the development of components that have to be able to withstand high vibrating stresses without losing performance or safety. The lightweight, thermally stable, and mechanically robust properties of GO and CNTs make them ideal for automotive and aerospace applications.[106,107,108] Supercapacitors based on GO/S and Gd-CNTs exhibit vibration resistance and reliable performance in UAV systems.[106] These materials offer both aerodynamic and energetic optimization for advanced platforms.

The development of composite materials in automobile body panel, interior parts, and aerospace industries contributes significantly to the effective performance and does not violate the structure in different axes of the environmental contexts. Automobile industry is experiencing an increased demand of bio-composites made of renewable materials. The evolution of natural fiber-reinforced polymer composites evidences the commitment of the industry to be more sustainable without loss of any core mechanical properties needed to be used in cars.[109] This further emphasizes on the trend on the use of environmentally friendly materials and is associated with the gradual growth in customer needs of being environmentally sustainable in the automobile industry.

Table 6 summarizes the key directions in the development and application of advanced materials and joining technologies within the automotive and aerospace industries. The focus is placed on composite systems, hybrid natural-synthetic fiber structures, and intelligent selection tools that enable enhanced mechanical performance, lightweight design, and sustainability. Each material or technique is associated with specific functional advantages and application areas, reflecting the industry's response to evolving technical and environmental demands. The classification serves as a foundation for understanding current innovations and guiding future material selection strategies in high-performance engineering contexts.

Table 6. Advanced Composite Materials and Smart Technologies in Automotive and Aerospace Applications

Section	Material/Technology	Core Function/Advantage	Typical Application
Lightweight and High Strength Materials	Carbon Fiber Reinforced Composites (CFRCs)	High strength-to-weight ratio, corrosion resistance	Aircraft frames, automotive chassis
Surface Treatment and Bonding	Hybrid Carbon-Bamboo Composites	Vibration damping, acoustic insulation	Interior parts, sound-sensitive zones
Surface Treatment and Bonding	Silane Treatment, Polymer Blending	Enhances interfacial adhesion, improves mechanical performance	Composite laminate interfaces, lightweight panels
Joining and Welding Technologies	Composite Laminate Interface Optimization	Enhanced structural bonding, crack resistance	Structural components in vehicles & aircraft
Bio-based and Sustainable Composites	Natural Fiber-Reinforced Polymers (NFRPs), e.g., flax, hemp	Renewable, biodegradable, lightweight	Door panels, dashboards, car interiors

Joining and Welding Technologies	Friction Stir Welding (FSW) of Al-Mg alloys	Solid-state joining, strong and ductile joints	Aerospace panels, EV battery enclosures
Smart Materials & Predictive Tools	Artificial Intelligence (AI), Machine Learning	Real-time performance prediction, material optimization	Material selection platforms, digital twin models
Acoustic and Vibration Properties	Bamboo-based hybrid composites, damping-focused resins	Noise and vibration reduction under dynamic load	Suspension systems, cabin walls
Environmental and Customer Trends	Bio-composites, recyclable polymer matrices	Sustainable, responds to consumer eco-awareness	Eco-cars, light utility vehicles

To conclude, recent developments in material science are triggering a radical change in the automotive and aerospace industries. The emphasis in ultra-light and ultra-high-performance composites, coupled with innovative in-manufacturing technology (additive manufacturing and advanced welding processes) has the potential to treat the demands of modern and more challenging engineering needs. As industries strive to find a balance amongst performance, safety and sustainability, future of vehicle and aircraft design will inevitably depend on the further improvement of material characteristics.

CONCLUSIONS

The unfettered power quality with high charging and discharging rates has made the graphene-based supercapacitors an interesting development in the energy storage technology. The basic knowledge of charge storage mechanisms lies in the differentiation between the electric double-layer capacitors (EDLCs) and pseudo capacitors, which have both advantages and disadvantages. EDLCs cycling is based on electrostatic forces, and pseudo capacitors offer high energy densities, which is based on redox-active materials. The main characteristics of supercapacitors are also their high values of specific capacitance, energy and power density, and cyclic stability that are required signs of performance. The graphene provides a solid platform due to its large surface area (~2630 m^2/g), highly electrically conductive, mechanical flexibility, and electrochemical stability. Such characteristics facilitate ion transport and charge accumulation and there is an excellent prospect of graphene as a high-performance electrode. There are numerous methods of manufacturing that have been designed to allow us to produce carefully customized varieties of the material that is defined as graphene according to the specifics of unique designs of devices, such as chemical vapor deposition (CVD), the Hummers method and liquid phase exfoliation. Further we would expect better industrial use of composites involving carbon nanotubes (CNTs), metal oxides, or conductive polymers, which give out different synergies in, e.g., increased conductivity, mechanical strength, or pseudo-capacitance. On the device terms, symmetric and asymmetric designs have been discussed to maximize the voltage and energy generation. Additionally, emergence of solid-state and bendable architecture presents new opportunities toward integration with modern electronics and smart wearable devices. Such developments respond to the increased demand of small, low-weight, and mechanically strong energy storing solutions. Graphene-based supercapacitors have been put into numerous applications such as in the sector of small-scale portable grids and in the energy storage system of large-scale grids stabilization. They offer energy storage and regenerative braking of lightweight, high-performance systems within the automotive industry and the aerospace industry. Moreover, the hybrid supercapacitor batteries are becoming trendy and offer a tradeoff among power and long-term energy storage to the extent that is essential to modern energy management technology. Intersection of material science of graphene with

engineering of supercapacitor is a high point of this field in the path to creating high-capacity, sustainable, and efficient energy storage devices. The next stage within the development of synthesis methods, composite design and integration of devices will increase their usability in a broad range of new energy systems.

BIBLIOGRAPHIC REFERENCES

1. Shahzad M, Ahmad F, Ibraheem M, Shakoor A, Ramay S, Raza M, Atiq S. Tuning diffusion coefficient, ionic conductivity, and transference number in rgo/bacoo3 electrode material for optimized supercapacitor energy storage. RSC Adv. 2025;15(8):6308-23. https://doi.org/10.1039/d4ra08894h

2. Li R, Yan X, Chen L. 2d conductive metal–organic frameworks for electrochemical energy application. Org Mater. 2024;06(02):45-65. https://doi.org/10.1055/s-0044-1786500

3. Khasim S, Pasha A, BN R, Prathibha B, P.R K. Facile synthesis of samarium (Sm 3+) doped cobalt-iron oxide nano ferrite as an advanced electrode material for supercapacitor applications. 2024. https://doi.org/10.21203/rs.3.rs-4177651/v1

4. Bandara T, Alahakoon A, Albinsson I, Mellander B. Activated carbon synthesized from jack wood biochar for high performing biomass derived composite double layer supercapacitors. 2024. https://doi.org/10.2139/ssrn.4724279

5. Madhushani K, Perera A, Lin W, Sultana J, Mishra S, Pérez F, Gupta R. High-performance supercapacitors using nanostructured polyaniline-based carbon: effect of electrolytes. Energy Storage. 2024;6(5). https://doi.org/10.1002/est2.70009

6. Essa M, Ali M, El-Kholy E, Amer M, Elsisi M, Sajjad U, Hamid Kh, El-sayed Awad H, Awad H. Improving micro-grid management: a review of integration of supercapacitor across different operating modes. Heliyon. 2025;11(3):e42178. https://doi.org/10.1016/j.heliyon.2025.e42178

7. Vinothini S, Keyan A, Sakthinathan S, Chiu T, Vittayakorn N. CuFe2O4 nanofiber incorporated with a three-dimensional graphene sheet composite electrode for supercapacitor and electrochemical sensor application. Inorganics. 2024;12(6):164. https://doi.org/10.3390/inorganics12060164

8. Masood M, Hussain S, Sohail M, Rehman A, Uzzaman M, Alnaser I, Karim MR, Wahab M. Recent progress, challenges, and opportunities of conducting polymers for energy storage applications. Chemistryselect. 2024;9(23). https://doi.org/10.1002/slct.202302876

9. Shahid S, Ali A. Study of structural, optical and electrical properties of zn- doped mos 2 nanomaterials for their supercapacitor applications. 2024. https://doi.org/10.21203/rs.3.rs-3996911/v1

10. Priya S, Salmataj S, Anusha B, Bhat P. Synthesis, characterisation of agricultural biomass derived activated carbon and its applications. Mater Res Express. 2025;12(1):012001. https://doi.org/10.1088/2053-1591/ada234

11. Kumar S, Singh D, Singh A, Srivastava M, Kumar S, Singh R, Yadav T, Alheety MA, Singh P. Waste peanut shells derived activated carbon for dual electrochemical applications. Energy

Storage. 2024;6(1). https://doi.org/10.1002/est2.571

12. Begum R, Goswami S, Kundu S, Kabir R, Das S, Bhattacharya D, Sikh AH, Ghosh C. Enhancement of the pseudocapacitive performance of iron hexacyanoferrate through porosity engineering: fabrication of an environment-friendly symmetric coin-cell. New J Chem. 2025;49(12):4780-92. https://doi.org/10.1039/d4nj05154h

13. Sultana S, Rahaman M, Hassan A, Parvez M, Chandan M. Biomass-based sustainable graphene for advanced electronic technology: a review. Chem Asian J. 2025;20(9). https://doi.org/10.1002/asia.202500128

14. Li H, Han Y, Qiu P, Qian Y. Plasma-assisted preparation of reduced graphene oxide and its applications in energy storage. Nanomaterials. 2024;14(23):1922. https://doi.org/10.3390/nano14231922

15. Avudaiappan S, et al. Experimental investigation on the influence of sonication parameter for enhancing the mechanical properties of cement mortar with graphene oxide integration. Mater Res Express. 2025;12(4):045602. https://doi.org/10.1088/2053-1591/adc2d7

16. Zong H, et al. Effect of static pressure on ultrasonic liquid phase exfoliation of few-layer graphene. Ultrason Sonochem. 2024;105:106863. https://doi.org/10.1016/j.ultsonch.2024.106863

17. Abaszade RG, Kapush OA, Nabiyev AM. Properties of carbon nanotubes doped with gadolinium. J Optoelectron Biomed Mater. 2020;12(3):61–5. https://www.chalcogen.ro/61_AbaszadeRG.pdf

18. Abaszade RG, Aliyev EM, Mammadov AG, Khanmamedova EA, Guliyev AA, Aliyev FG, Zapukhlyak RI, Budak HF, Kasapoglu AE, Margitych TO, Singh A, Arya S, Gür E, Stetsenko MO. Investigation of thermal properties of gadolinium doped carbon nanotubes. Phys Chem Solid State. 2024;25(1):142–7. https://doi.org/10.15330/pcss.25.1.142-147

19. Abaszade RG, Mammadova SA, Kapush OA, Agayev FG, Nabiev AM, Mammadova MM, Budzulyak SI, Kotsyubynsky VO. Synthesis and characterization of graphene oxide flakes for transparent thin films. Phys Chem Solid State. 2021;23(3):595–601. https://doi.org/10.15330/pcss.22.3.595-601

20. Abaszade RG, Aliyev EM, Babanli MB, Kotsyubynsky VO, Zapukhlyak RI, Mamedov AG, Budak HF, Kasapoglu AE, Gur E, Margitych TO, Stetsenko MO. Investigation of thermal properties of carbon nanotubes and carboxyl group-functionalized carbon nanotubes. Phys Chem Solid State. 2023;24(3):530–5. https://doi.org/10.15330/pcss.24.3.530-535

21. Abaszade RG, Mammadov AG, Khanmamedova EA, Aliyev FG, Kotsyubynsky VO, Gür E, Soltabayev BD, Margitych TO, Stetsenko MO, Singh A, Arya S. Photoconductivity of functionalized carbon nanotubes. Dig J Nanomater Biostruct. 2024;19(2):837–43. https://doi.org/10.15251/DJNB.2024.192.837

22. Khokhar S, Chand P, Anand H. Ctab-assisted hydrothermal synthesis of micro-sheets like ni-bdc electrode material for supercapacitor application. Phys Scr. 2025;100(3):035957. https://doi.org/10.1088/1402-4896/adb45c

23. Meghanathan K, Parthibavarman M. Investigation of the electrochemical properties of desert rose-like zif-67/nicote hybrid composite as asymmetric supercapacitors for energy storage applications. 2024. https://doi.org/10.21203/rs.3.rs-3844900/v1

24. Dhapola P, et al. Environment-friendly approach for synthesis of promising porous carbon: empowering supercapacitors for a sustainable future. Mater Adv. 2024;5(6):2430-40. https://doi.org/10.1039/d3ma00984j

25. Liu W, Yuan G, Jiang S, Shi Y, Pang H. Two-dimensional (2d) conductive metal-organic framework thin films: the preparation and applications in electrochemistry. Chem Eur J. 2024;30(70). https://doi.org/10.1002/chem.202402747

26. Gu Y, et al. Carbon nanofibers as supporting substrate for growth of polyaniline nanorods on fe2o3 nanoneedles toward electrochemical energy storage. ACS Omega. 2024;9(51):50237-45. https://doi.org/10.1021/acsomega.4c05727

27. Wang Q, et al. A multipurpose 1d/2d nitrogen-doped nanocarbon hybrid evolved from an anthracite-based graphene oxide-co-melamine template. ACS Appl Electron Mater. 2024;6(4):2594-608. https://doi.org/10.1021/acsaelm.4c00191

28. Anand S, Madhushree R, Devi K, Pinheiro D. Synergistic pseudocapacitive behavior of cr2ctx mxene and cu-ptc mof in cm-ii: an electroactive composite. Nano Express. 2025;6(2):025006. https://doi.org/10.1088/2632-959x/add02f

29. Abaszade RG, Babanli MB, Kotsyubynsky VO, Mammadov AG, Gür E, Kapush OA, Stetsenko MO, Zapukhlyak RI. Influence of gadolinium doping on structural properties of carbon nanotube. Phys Chem Solid State. 2023;24(1):153–8. https://doi.org/10.15330/pcss.24.1.153-158

30. Li L, et al. Facile synthesis of n-doped porous carbon materials derived from bombyx mori silk for high-performance symmetric supercapacitors. Chem Eur J. 2025;31(22). https://doi.org/10.1002/chem.202404569

31. Zhao C, et al. Hierarchical porous co-mn hexacyanoferrate for advanced aqueous sodium-ion hybrid supercapacitors. J Electrochem Soc. 2025;172(1):010517. https://doi.org/10.1149/1945-7111/ada73d

32. Abaszade RG, Mammadov AG, Bayramov IY, Khanmammadova EA, Kotsyubynsky VO, Kapush OA, Boychuk VM, Gur EY. Structural and electrical properties of sulfur-doped graphene oxide/graphite oxide composite. Phys Chem Solid State. 2022;25(2):256–60. https://doi.org/10.15330/pcss.23.2.256-260

33. Guliyeva NA, Abaszade RG, Khanmammadova EA, Azizov EM. Synthesis and analysis of nanostructured graphene oxide. J Optoelectron Biomed Mater. 2023;15(1):23–30. https://doi.org/10.15251/JOBM.2023.151.23

34. Figarova SR, Aliyev EM, Abaszade RG, Alekberov RI, Figarov VR. Negative differential resistance of graphene oxide–sulphur compound. J Nano Res. 2021;67:25–31. https://doi.org/10.4028/www.scientific.net/JNanoR.67.25

35. Papadiamantis A, et al. A systematic review on the state-of-the-art and research gaps regarding inorganic and carbon-based multicomponent and high-aspect ratio nanomaterials. Comput Struct Biotechnol J. 2024;25:211-29. https://doi.org/10.1016/j.csbj.2024.10.020

36. Lu Y, Tsai M, Lin C, Woon W, Lin C. Nanoscopic supercapacitance elucidations of the graphene-ionic interface with suspended/supported graphene in different ionic solutions. ACS Appl Mater Interfaces. 2025;17(3):5419-29. https://doi.org/10.1021/acsami.4c16362

37. Salehfar S, Azami M. Asymmetric electronic deformation in graphene molecular capacitors. Int J Quantum Chem. 2024;124(12). https://doi.org/10.1002/qua.27426

38. Obodo R, et al. Investigating the dual synergistic amalgamation of CeO2@Wo3/GO electrodes for supercapacitor application. Energy Storage. 2024;6(5). https://doi.org/10.1002/est2.70020

39. Manik Y, Goh B, Siburian R, Alias Y. Synthesis of graphene nanosheets from coconut and candlenut shells: large-scale production and application in Fe ion adsorption and electrochemical properties. ACS Omega. 2025;10(4):3338-50. https://doi.org/10.1021/acsomega.4c05745

40. Qi Z, et al. Flexible supercapacitor with wide electrochemical stable window based on hydrogel electrolyte. Small. 2024;20(33). https://doi.org/10.1002/smll.202400369

41. Zhang Q, Li G, Qiao F. Recent advances in integrated solar cell/supercapacitor devices: fabrication, strategy and perspectives. J Adv Res. 2025;67:197-215. https://doi.org/10.1016/j.jare.2024.01.032

42. Hossain M, Kosei O. Detection of ultraviolet light by graphene oxide derived from epitaxial graphene on sic and graphite. ACS Omega. 2024. https://doi.org/10.1021/acsomega.4c03882

43. Yousri N, El-Feky H, Nassar M, Amin A. Nanoscale zero-valent silver and graphene oxide nanoparticles: facile synthesis and characterization. Asian J Chem Sci. 2024;14(3):63-70. https://doi.org/10.9734/ajocs/2024/v14i3310

44. Abaszade RG, Mammadov AG, Bayramov IY, Khanmammadova EA, Kotsyubynsky VO, Gur EY, Kapush OA. Modeling of voltage–ampere characteristic structures on the basis of graphene oxide/sulfur compounds. Tech Phys Probl Eng. 2022;14(2):302–6.

45. Jayan J, Deeraj B, Joseph K, Saritha A. Designed and tailor-made double hydrophilic block copolymer-graphene nanoplatelet hybrids for reinforcing epoxy thermosets. Sci Rep. 2024;14(1). https://doi.org/10.1038/s41598-024-59322-x

46. Pincot A, et al. Rheological, electrochemical, and microstructural properties of graphene oxides as flowable electrodes for energy storage applications. RSC Adv. 2025;15(12):9190-207. https://doi.org/10.1039/d4ra08308c

47. Xu Y, Di M, Liu J, Li Z, Wang Y, Tang N. Enhancing visible-light absorption of 2d carbon nitride by constructing 2d/2d van der waals heterojunctions of carbon nitride/nitrogen-superdoped graphene. ACS Omega. 2024;9(4):4804-10. https://doi.org/10.1021/acsomega.3c08308

48. Wang K, et al. Functionalization of graphene nanosheets-3d printing resins for improvement

of mechanical properties and thermal conductivity. ACS Appl Polym Mater. 2024;6(18):11549-56. https://doi.org/10.1021/acsapm.4c02181

49. Yuan J, Zhang Y, Chen F, Gu Z. An overview of joule heating in energy storage materials and applications. J Mater Chem C. 2024;12(37):14729-53. https://doi.org/10.1039/d4tc01736f

50. Zare-Zardini H, Saberian E, Jenča A, Petrášová A, Jenčová J. A narrative review on the promising potential of graphene in vaccine design: evaluating the benefits and drawbacks of carbon nanoplates in nanovaccine production. Vaccines. 2024;12(6):660. https://doi.org/10.3390/vaccines12060660

51. Sial Q, Safder U, Iqbal S, Ali R. Advancement in supercapacitors for IOT applications by using machine learning: current trends and future technology. Sustainability. 2024;16(4):1516. https://doi.org/10.3390/su16041516

52. Stetsenko MO, Abaszade RG. X-ray phase analysis of carbon nanotubes obtained by the arc discharge method. UNEC J Eng Appl Sci. 2023;3(1):15–20. https://doi.org/10.61640/ujeas.2023.0503

53. Abaszade RG, Mammadova AG, Khanmammadova EA, Bayramov İY, Namazov RA, Popal KhM, Melikova SZ, Qasımov RC, Bayramov MA, Babayeva Nİ. Electron paramagnetic resonance study of gadolinium doped graphene oxide. J Ovonic Res. 2023;19(2):259–63. https://doi.org/10.15251/JOR.2023.193.259

54. Arnal T, Eisenberg P, Abad M, Ares-Pernas A, Bernal C. Exploring the mechanical, rheological, and thermal performance of self-reinforced composites based on polyamides and multi-walled carbon nanotubes. J Appl Polym Sci. 2024;141(23). https://doi.org/10.1002/app.55471

55. Abaszade RG, Kapush OA, Mamedova SA, Nabiyev AM, Melikova SZ, Budzulyak SI. Gadolinium doping influence on the properties of carbon nanotubes. Phys Chem Solid State. 2020;21(3):404–8. https://doi.org/10.15330/pcss.21.3.404-408

56. Yasmeen A, et al. High-performance rgo@cnts@agnbs nanocomposite electrode material for hybrid supercapacitor and electrochemical glucose sensor. Phys Scr. 2024;99(4):045965. https://doi.org/10.1088/1402-4896/ad3152

57. Le N, et al. An optimized mno2-ag nanocomposite-based sensing platform for determination of 4-nitrophenol in tomato samples: influences of morphological aspect of mno2 nanostructures and synergic effect on electrochemical kinetic parameters and analytical performance. J Electrochem Soc. 2024;171(5):057504. https://doi.org/10.1149/1945-7111/ad45c6

58. Zhang Q, Wang H, Chen S, Liu X, Liu J, Liu X. Proton hydrogel-based supercapacitors with rapid low-temperature self-healing properties. ACS Appl Mater Interfaces. 2024;16(31):40980-91. https://doi.org/10.1021/acsami.4c07421

59. Chowdhury N, Sun J, Cahill D. Anisotropic thermal conductivity of kapton films, composites, and laminates. ACS Appl Polym Mater. 2025;7(3):1440-7. https://doi.org/10.1021/acsapm.4c03181

60. Zhang M, et al. Novel polymer/halloysite composites with high halloysite content and remarkable mechanical strength. RSC Appl Interfaces. 2025;2(2):410-9. https://doi.org/10.1039/d4lf00356j

61. Jing L, et al. The mass-balancing between positive and negative electrodes for optimizing energy density of supercapacitors. J Am Chem Soc. 2024;146(21):14369-85. https://doi.org/10.1021/jacs.4c00486

62. Dutta P, et al. Activating ion channels in collapsed hydrogel derived densified mxene films with cellulose nanofibers to overcome the areal versus volumetric capacitance trade-off. Small. 2024;20(35). https://doi.org/10.1002/smll.202400119

63. Liang X, Tang L, Zhang Y, Zhu X, Gao J. Robust graphene-based aerogel for integrated 3d asymmetric supercapacitors with high energy density. Chem Asian J. 2024;19(10). https://doi.org/10.1002/asia.202400243

64. Abaszade R, Khanmammadova E. Specific applications for unmanned aerial vehicles (UAVs) and aerial robotics. In: Advanced antenna technologies for aerial platforms: From design to deployment. 2025. p. 117–58.

65. He Y, et al. In situ solid-phase synthesis of CoZnSe/CNT nanocomposites for high-performance sodium-ion energy storage devices. ACS Appl Energy Mater. 2024;7(19):8489-502. https://doi.org/10.1021/acsaem.4c01415

66. Ali A, et al. Recent progress in metal oxide-based electrode materials for safe and sustainable variants of supercapacitors. Front Chem. 2024;12. https://doi.org/10.3389/fchem.2024.1402563

67. Bilal M, et al. Investigating electrochemical behavior of cobalt pentacyano(methylaniline) ferrate(ii) in various aqueous electrolytes for supercapacitor application. New J Chem. 2024;48(27):12434-43. https://doi.org/10.1039/d4nj02023e

68. Murugan M, Dineshkumar G, Ganesan M, Sahoo N, Sivanantham M. Influence of phosphoric acid activation on physiochemical characteristics of activated carbons and their performance as supercapacitor. Energy Storage. 2024;6(7). https://doi.org/10.1002/est2.70050

69. Paul A, Dey S, Goswami G, Chakraborty A, Murmu N, Kuila T. Asymmetric aqueous supercapacitor based on zinc oxide-manganese oxide cathode material and Fe—Ni oxide/reduced graphene oxide anode material. Adv Sustain Syst. 2024;9(4). https://doi.org/10.1002/adsu.202400329

70. Merces L, et al. Bio-inspired dynamically morphing microelectronics toward high-density energy applications and intelligent biomedical implants. Adv Mater. 2024;36(26). https://doi.org/10.1002/adma.202313327

71. Moradi R, Pour Khalili N, Khanmamadova E, Abaszade R. Functionalized carbon nanostructures for flexible electronics. In: Barhoum A, Deshmukh K, editors. Handbook of functionalized carbon nanostructures. 2024. p. 2581–614. https://doi.org/10.1007/978-3-031-14955-9_71-1

72. Khanmamadova E, Abaszade R. Specific applications for unmanned aerial vehicles (UAVs) and aerial robotics. In: Advanced antenna technologies for aerial platforms: From design to deployment. 2025. p. 117–58.

73. Khanmamadova E, Abaszade R. Advanced design, materials, and manufacturing techniques for next-generation antennas. In: Advanced antenna technologies for aerial platforms: From design to deployment. 2025. p. 49–92. https://doi.org/10.4018/979-8-3693-6035-4

74. Khanmamadova E, Abaszade R, Moradi R. Hydrophobic and hydrophilic behavior of multifunctional thin film. In: Multi-scale and multifunctional coatings and interfaces for tribological contacts. 2025. p. 83–102. https://doi.org/10.1201/9781032635347-6

75. Khanmamadova E, Abaszade R, Moradi R. Antiviral thin surface and surface life. In: Multi-scale and multifunctional coatings and interfaces for tribological contacts. 2025. p. 121–34. https://doi.org/10.1201/9781032635347-8

76. Xiong S, et al. Preparation of Ni nanowires covalent organic framework composites with high electrochemical stability and supercapacitor performance. J Phys Chem C. 2024;128(23):9435-45. https://doi.org/10.1021/acs.jpcc.4c01332

77. Shi X, et al. A dual-carbon potassium-ion capacitor enabled by hollow carbon fibrous electrodes with reduced graphitization. Adv Mater. 2024. https://doi.org/10.1002/adma.202406794

78. Heiba A, elsalam m, Yoon T, Sawy E. Zr-Mof composites with zipped and unzipped carbon nanotubes for high-performance electrochemical supercapacitors. Nanoscale. 2025;17(1):459-73. https://doi.org/10.1039/d4nr03926b

79. Yan Y, Sun W, Wei Y, Liu K, Jing J, Hu G. Review of biomass-derived carbon nanomaterials—from 0d to 3d—for supercapacitor applications. Nanomaterials. 2025;15(4):315. https://doi.org/10.3390/nano15040315

80. Saleh A, et al. Cellulose-based conductive materials for bioelectronics. Chemsuschem. 2024;18(6). https://doi.org/10.1002/cssc.202401762

81. Daniel S, M.G P, E.M. M. Scouting the supercapacitor performance of bimetallic transition metal co-doped carbon quantum dots (cqds) polyvinyl alcohol (pva) composites as green electrode materials. 2024. https://doi.org/10.21203/rs.3.rs-3922917/v1

82. Tan N, et al. Biomass-derived carbon materials for smart electronics: insights from wood pitch-based microsupercapacitors. Adv Funct Mater. 2024;35(1). https://doi.org/10.1002/adfm.202411596

83. Liu L, Zhang X, Liu Y, Gong X. Electrochemical energy storage devices—batteries, supercapacitors, and battery–supercapacitor hybrid devices. ACS Appl Electron Mater. 2025;7(6):2233-70. https://doi.org/10.1021/acsaelm.5c00069

84. Banerjee H, Grey C, Morris A. Stability and redox mechanisms of ni-rich nmc cathodes: insights from first-principles many-body calculations. Chem Mater. 2024;36(13):6575-87.

https://doi.org/10.1021/acs.chemmater.4c00928

85. Ravindran B, et al. Tungsten diselenide WSe2@pvp polymer composite supercapacitors: development of energy storage capabilities. Polym Adv Technol. 2025;36(4). https://doi.org/10.1002/pat.70157

86. Suneetha V, Mahesh V, Potu S, Madathil N, Kumar K, Kumar R. Facile and robust high-performance triboelectric nanogenerator based on electronic waste for self-powered electronics. Energy Technol. 2024;13(1). https://doi.org/10.1002/ente.202401387

87. Afif M, Pratiwi V, Noerochim L. Enhanced ionic conductivity of fluoride-doped liti2(po4)3 as solid electrolyte of lithium-ion battery. Eng Chem. 2024;5:37-42. https://doi.org/10.4028/p-frje6w

88. Liu J, Xia Q, Wang L, Hu Q, Shinde N, Zhou A. In situ growth of nanorod-shaped Ni,Co-MOF on MO2CTX mxene surface to realize enhanced energy storage for supercapacitors. ACS Appl Mater Interfaces. 2024;16(37):49380-91. https://doi.org/10.1021/acsami.4c09616

89. Jing X, Ji L, Xie H. Bi-level inverse robust optimization dispatch of wind power and pumped storage hydropower complementary systems. Processes. 2024;12(4):729. https://doi.org/10.3390/pr12040729

90. Chen Y, et al. Hybrid interface chemistry enabling mixed conducting via ultrafast microwave polarization toward dendrite-free Zn anodes. Small. 2024;20(32). https://doi.org/10.1002/smll.202401249

91. Zou Y, Yang X, Wei L, Tong W, Yang S, Jin L. Effect of tab configuration on large-format battery performance based on three-dimensional electrochemical-thermal coupled model. IOP Conf Ser Earth Environ Sci. 2025;1500(1):012019. https://doi.org/10.1088/1755-1315/1500/1/012019

92. Abaszade RG, Mammadov AG, Khanmammadova EA. Fundamentals of thermal management in renewable energy systems. In: Heat exchanger technologies for sustainable renewable energy systems. 2025. p. 52–72. https://doi.org/10.1201/9781003534785-2

93. Sun Y, Yang Z, Li W, Ganin A. The investigation of co6−xfexw6n (x = 0, 3, 6) as electrocatalysts for the hydrogen evolution reaction. Dalton Trans. 2025;54(13):5577-83. https://doi.org/10.1039/d4dt03005b

94. Iksan N, Purwanto P, Sutanto H. Real-time monitoring of photovoltaic systems and control of electricity supply for smart micro Grid-PV using IOT. TEM J. 2024:514-23. https://doi.org/10.18421/tem131-53

95. Niu W, Tan M, Li H, Chen C, Xue G, Zhu X, … Xu Z. A model for renewable-based power system simulation in the context of electricity trading market. 2024;452. https://doi.org/10.1117/12.3025096

96. Liu Y, et al. Molten salt construction of nitrogen, oxygen, sulfur Co-doped hierarchical porous carbon for Zinc ION hybrid capacitors. Adv Sustain Syst. 2025;9(3). https://doi.org/10.1002/adsu.202401000

97. Zhu J, Huang T, Lu M, Qiu X, Zhang W. Sustainable lignin-derived hierarchical mesoporous carbon synthesized by a renewable nano-calcium carbonate hard template method and its utilization in zinc ion hybrid supercapacitors. Green Chem. 2024;26(9):5441-51. https://doi.org/10.1039/d4gc00323c

98. Sivakumar P, et al. Mof-derived nickel cobaltite: a pathway to enhanced supercapacitor performance. J Mater Chem A. 2025;13(8):5961-73. https://doi.org/10.1039/d4ta06866a

99. Lu J, et al. Nanoconfined carbonization enabling high-density porous carbon for jointly superior gravimetric and volumetric Zinc-Ion storage. Energy Environ Sci. 2024;17(18):6833-43. https://doi.org/10.1039/d4ee02163k

100. Wen Z, Wang F. A novel wide-range voltage GAIN bidirectional dc-dc converter for electric vehicles. Int J Circuit Theory Appl. 2024;53(4):2020-42. https://doi.org/10.1002/cta.4191

101. Jo S, Tran D, Jabbar M, Kim M, Kim K. Continuous power management of decentralized dc microgrid based on transitional operation modes under system uncertainty and sensor failure. Sustainability. 2024;16(12):4925. https://doi.org/10.3390/su16124925

102. Yuan H, Ye Y, Yuan L, Chen Y, Sun L. Research on optimal method of hybrid energy storage capacity of microgrid in new energy internet environment. 2024. https://doi.org/10.1117/12.3015212

103. Zhang K, Lin X, Shi Y, Oyaizu K, Jia Z. Two-electron redox chemistry of nitroxide radicals: fundamental mechanisms and applications in energy storage. ACS Electrochem. 2025;1(2):123-37. https://doi.org/10.1021/acselectrochem.4c00119

104. Săftoiu G, Constantin C, Nicoară A, Pelin C, Ficai A. Glass fibre-reinforced composite materials used in the aeronautical transport sector: a critical circular economy point of view. Sustainability. 2024;16(11):4632. https://doi.org/10.3390/su16114632

105. Kudva A, Mahesha G, Hegde S, Pai D. Influence of chemical treatment of bamboo fibers on the vibration and acoustic characterization of carbon/bamboo fiber reinforced hybrid composites. Mater Res Express. 2024;11(7):075304. https://doi.org/10.1088/2053-1591/ad5cd5

106. Abaszade RG, Khanmammadova EA. Renewable energy sources and conversion technologies. In: Heat exchanger technologies for sustainable renewable energy systems. 2025. p. 52–72. https://doi.org/10.1201/9781003534785-3

107. Mammadov AG, Abaszade RG, Kotsyubynsky VO, Gur EY, Bayramov IY, Khanmammadova EA, Kapush OA. Photoconductivity of carbon nanotubes. Tech Phys Probl Eng. 2022;14(3):155–60.

108. Mammadov AG, Abaszade RG, Babanli MB, Kotsyubynsky VO, Gur E, Soltabayev BD, Margitych TO, Stetsenko MO. Photoconductivity of gadolinium-doped carbon nanotubes. Int J Tech Phys Probl Eng. 2023;15(3):53–8.

109. Musa A, Onwualu A. Potential of lignocellulosic fiber reinforced polymer composites for automobile parts production: current knowledge, research needs, and future direction. Heliyon. 2024;10(3):e24683. https://doi.org/10.1016/j.heliyon.2024.e24683

110. Khanmammadova EA, Abaszade RG. The evolution of green mobility: A critical comparison of pure electric and hybrid electric vehicles. In: Hybrid electric vehicles and distributed renewable energy conversion: Control and vibration analysis. 2025. p. 187–251. https://doi.org/10.4018/979-8-3693-5797-2.ch011

111. Singh A, Lalotra N, Shah SS, Rather MD, López-Maldonado EA, Pathania K, Abaszade RG, Stetsenko M, Arya S. A comprehensive review on the synthesis and properties of MXenes for supercapacitor applications. ACS Appl Energy Mater. 2025;8(8):4884–914. https://doi.org/10.1021/acsaem.4c03194

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