Graphene and Derivatives for Electrochemical Storage: Perspectives, Challenges, and Advanced Applications. A Literature Review

INSINGA MARIA GRAZIA[1,2], FILIPPO CAROLLO[1]
[1]Department of Engineering, Università degli Studi di Palermo,
Palermo,
ITALY

[2]Euro-Mediterranean Institute of Science and Technology,
Palermo,
ITALY

Abstract: - The shift toward cleaner power solutions requires electrochemical storage alternatives able to merge considerable energy concentration, power output, and long lifespan. Graphene and its associated structures have surfaced as notable candidates for advanced electrode compounds, because of their outstanding surface area, electrical flow, and structural pliability. Nevertheless, unaltered graphene frequently faces challenges such as layer re-stacking and reduced cycle reliability, which have prompted broad research into altered and composite materials. This overview meticulously scrutinizes fifty typical investigations published across the past decade, focusing on the role of graphene and its variants—like graphene oxide, "r-graphene oxide", heteroatom-laced graphene, and composite mixtures incorporating metal compounds, conductive plastics, and other 2D substances—for electrical energy retention. A specific focus is given to uses in supercapacitors and lithium-, sodium-, and zinc-ion cells, including combined and pliable units. The assessment emphasizes considerable advancements in capacitance, energy/power metrics, and stability over cycles, whilst also pointing out the major hurdles of bulk manufacturing, consistency, and economic viability [1]. In closing, the critique maps out forthcoming pathways, stressing the merging of graphene with new 2D substances, environmentally kind creation processes, and the design of adaptable energy-holding contraptions suitable for manufacturing and utility-scale deployment [2].

Key-Words: - Graphene-based materials, electrochemical energy storage, supercapacitors, lithium- and sodium-ion batteries, graphene derivatives (GO, rGO, doped graphene), hybrid nanocomposites

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1 Introduction

The worldwide need for adept energy storing methods has grown sharply in recent times, motivated by the extensive integration of sustainable power origins and the electrification of transit. Among the current technologies, rechargeable cells, supercapacitors, and combined systems have surfaced as primary remedies, each presenting particular strengths and drawbacks regarding energy concentration, output provision, and longevity [3], [4]. While lithium-ion accumulators are commonly acknowledged for their high energy density, supercapacitors distinguish themselves for their swift charging-discharging capacities, though with a trade-off in lower specific volume [5], [6]. In this scenario, the search for advanced electrode materials has become essential to overcome the intrinsic trade‑offs of conventional storage devices. Materials featuring high conductivity, tunable chemical structures, and large accessible surface areas are especially desirable to bridge the gap between high‑energy and high‑power requirements [7], [8]. Graphene and its derivatives have therefore attracted considerable attention, owing to their exceptional electronic, mechanical, and morphological properties, which make them ideal candidates for electrochemical energy storage [9], [10], [11]. Graphene, a two‑dimensional carbon allotrope made up of sp^2‑hybridized atoms, provides a theoretical surface area of more than 2600 $m^2 g^{-1}$, high electron mobility, and exceptional mechanical strength [12], [13]. These attributes are very advantageous for designing next‑generation electrodes in supercapacitors and batteries [14], [15]. Nevertheless, pristine graphene often faces significant drawbacks, particularly the propensity of nanosheets to restack into dense aggregates, which markedly reduces ion accessibility and active surface

area. To address these difficulties, various derivatives have been fashioned, such as graphene oxide (GO), reduced graphene oxide (rGO), heteroatom-doped graphene, and composite hybrids with metal oxides, conductive polymers, and novel two-dimensional substances [16], [17]. Given the quick advancements in this domain, a thorough and systematic reevaluation is necessary. The aim of this review is to prudently assess the recent progress in utilizing graphene and its counterparts for electrical power storage, with a distinct emphasis on material design techniques, performance indicators, and upcoming utilization possibilities. By looking over more than fifty crucial reports, this piece intends to highlight both the potential and the hurdles that need resolving to transform benchtop advances into commercially feasible technologies [18], [19].

2 Theoretical background

Graphene is a two-dimensional allotrope of carbon arranged in a honeycomb lattice of sp^2-hybridized atoms, acting as the foundational unit for other carbon nanostructures like fullerenes, carbon nanotubes, and graphite [3]. Its distinctive electronic arrangement, characterized by massless Dirac fermions, bestows upon graphene superb electrical conductance, while its theoretical surface area surpassing 2600 $m^2 g^{-1}$ provides numerous available locations for electrochemical processes [12]. The material also displays high mechanical strength and flexibility, essential for flexible and wearable storage device applications. However, pristine graphene faces drawbacks such as restacking and a scarcity of redox-active sites, which constrain its electrochemical performance [17]. To address these limitations, several variants and functionalized forms of graphene have been developed [20], [21]. Graphene oxide (GO), containing oxygen-rich functional groups, provides improved hydrophilicity and processability, though it reduces conductivity. Reduced graphene oxide (rGO), created by partially eliminating oxygen functionalities, recovers electrical conductivity whilst preserving structural imperfections beneficial for ion movement [16]. Heteroatom-doped graphene, incorporating nitrogen, boron, sulfur, or phosphorus, furnishes additional electroactive locations, modifies charge allocation, and boosts pseudocapacitive capability [18]. Hybrid graphene-based assemblies, blending graphene with metal oxides, sulfides, conductive polymers, or novel 2D materials (like MXenes), unite the conductivity and structural resilience of graphene with faradaic inputs from the added constituents [19], [22]. Electrochemical energy storage in these systems depends on two basic mechanisms. The first is the electrical double-layer capacitance (EDLC), where charge is stored electrostatically at the electrode/electrolyte interface with minimal chemical changes. Graphene, with its large surface area and conductivity, is especially suitable for EDLC, providing high power density and an extended cycle life [5]. The second mechanism is pseudocapacitance, involving rapid and reversible redox reactions on the surface or near-surface of electrode materials. Graphene derivatives—particularly doped variants and composites with transition-metal oxides or conducting polymers—are key for boosting pseudocapacitive contributions, thus increasing specific capacitance [7], [23]. In the context of batteries, graphene and its derivatives serve both as active materials and as conductive frameworks. In lithium-ion batteries (Li-ion), graphene improves electron transport, handles volume changes of alloying-type anodes (e.g., silicon, tin), and improves interface stability. In sodium-ion (Na-ion) and zinc-ion (Zn-ion) batteries, the structural adaptability and adjustable chemistry of graphene derivatives help address challenges like the sizable ionic radius of Na^+ or dendritic growth of Zn^{2+} [9]. In Figure 1 it is possible to see a graphical scheme summarizing the two main mechanisms, EDLC and pseudocapacitance, with examples of applications in supercapacitors and batteries.

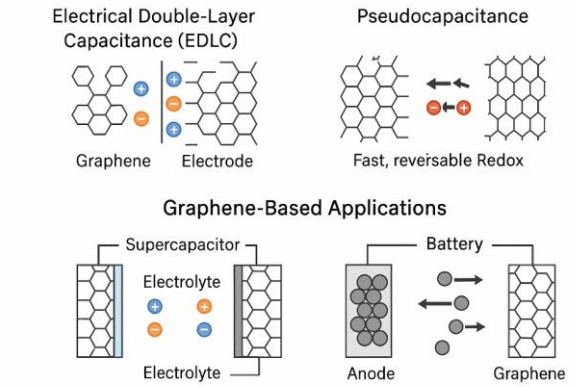

Fig. 1: Graphical scheme summarizing the two main mechanisms, EDLC and pseudocapacitance, with examples of a pplications in supercapacitors and batteries

To evaluate the performance of graphene-based materials, several key parameters are commonly used:

- Specific capacitance (F g^{-1}) or specific capacity (mAh g^{-1}), which reflect the charge storage capability per unit mass;

- Energy density (Wh kg^{-1}), defining how much energy can be stored;
- Power density (W kg^{-1}), indicating how quickly energy can be delivered;
- Cycling efficiency and stability, which determine the lifetime of the device.

Together, these parameters provide a comprehensive framework for comparing the varied architectures and chemistries of graphene based electrodes and for evaluating their potential in next generation energy storage devices.

As summarized in Table 1, the comparison among pristine graphene and its derivatives highlights how structural modifications significantly affect electrochemical performance.

Table 1. Comparison among pristine graphene and its derivatives

Material	**Structure**	**Surface area**	**Electrical conductivity**	**Key limitations**
Pristine Graphene	Single-layer sp^2 carbon network; honeycomb lattice	Theoretical: 2630 m^2/g; reduced by restacking	Very high (~10^6 S/m)	Restacking, lack of active sites for redox
Graphene Oxide (GO)	Graphene sheets with abundant oxygen functional groups (hydroxyl, carboxyl, epoxy)	Moderate; functional groups improve wettability	Low (due to disrupted sp^2 network)	Poor conductivity, instability under cycling
Reduced Graphene Oxide (rGO)	Partially reduced GO, defects preserved, fewer oxygen groups	Moderate to high; defect-rich, accessible pores	Restored conductivity, lower than pristine graphene	Partial reduction leads to structural defects
Doped Graphene (N, B, S, P)	Enhanced or tunable depending on dopant type and configuration	Comparable to rGO; dopants improve active site distribution	Enhanced or tunable depending on dopant type and configuration	Complex synthesis, stability of doped configurations
Graphene Hybrids (with oxides/polymers/2D materials)	Graphene combined with metal oxides, sulfides, conducting polymers, MXenes, etc.	Variable; tailored via structural design (3D porous frameworks)	Intermediate; depends on secondary component	Scalability, reproducibility, cost of hybridization

While pure graphene is noted for outstanding theoretical conductance and surface expanse, its real-world application is limited by sheet restacking and a scarcity of abundant electroactive locations. Graphene oxide, abundant with oxygen functional moieties, presents improved workability and wettability but endures diminished electrical conduction. Reduced graphene oxide somewhat regains conductance and presents ion routes linked to defects, though structural imperfections remain. Heteroatom-doped graphene offers further active locations and improved charge dispersal, but its preparation is typically complex and hard to scale up. Ultimately, hybrid graphene-based composites merge graphene's intrinsic conductance with faradaic inputs from metal oxides, sulfides, or conductive plastics, resulting in synergistic boosts while also raising production intricacy and costs. Collectively, these findings emphasize the significance of tailored material configurations that stabilize conductance, surface accessibility, and resilience, thereby improving graphene-based anodes for genuine electrochemical power saving purposes.

2.1 Quantitative Electrochemical Framework

Electrochemical performance in graphene-based electrodes should be evaluated using quantitative descriptors that allow consistent comparison across materials and device configurations. The Coulombic efficiency (CE), which reflects reversibility and parasitic side reactions, is defined as:

$$\eta = \frac{Q_{discharge}}{Q_{charge}} \; X \; 100\% \; (1)$$

Values of η approaching 100% indicate highly reversible charge storage, while deviations reflect electrolyte decomposition, solid–electrolyte interphase (SEI) growth, or irreversible ion trapping.

In graphene-based systems, CE is strongly influenced by defect density and interfacial chemistry. For full-cell configurations, charge balance between electrodes must be satisfied:

$$m_+C_+ \approx m\_C\_ \ (2)$$

where □ is the mass loading and □ is the specific capacity of positive (+) and negative (−) electrodes. Many literature reports are based on half-cell testing and may overestimate practical performance if this balance is not considered. It is also essential to distinguish between different capacity metrics:

- Gravimetric capacity (mAh g^{-1}, based on active material mass)
- Areal capacity (mAh cm^{-2}, based on electrode area)
- Volumetric capacity (mAh cm^{-3}, based on electrode volume)

Most graphene-based studies report gravimetric values referred only to active material mass, which does not fully reflect device-level performance.

2.2 Diffusion and Rate Capability Descriptors

Ion transport in porous graphene architectures can be described using Fick's laws. Fick's first law:

$$J = -D\frac{dC}{dx} \ (3)$$

Fick's second law:

$$\frac{\partial C}{\partial t} = -D\frac{\partial^2 C}{\partial x^2} \ (4)$$

The characteristic diffusion time is approximated by:

$$t = \frac{L^2}{D} \ (5)$$

where L is the diffusion length and D is the ion diffusion coefficient. Three-dimensional graphene architectures reduce the effective diffusion length □, while mesoporosity enhances electrolyte accessibility, effectively increasing □. Defect engineering and heteroatom doping introduce additional ion pathways, contributing to improved rate capability.

2.3 Impedance and Interfacial Resistance Modeling

Electrochemical impedance spectroscopy (EIS) is commonly interpreted using equivalent circuit models composed of: Rs – Rct – Cdl – Zw

Where:

- Rs = solution resistance
- Rct = charge-transfer resistance
- Cdl = double-layer capacitance
- Zw = Warburg diffusion impedance

The Warburg impedance is frequency dependent:

$$Z_W \propto \omega^{-\frac{1}{2}} \ (6)$$

A reduction in Rct indicates improved interfacial charge transfer, while a diminished Warburg component reflects enhanced ion diffusion. In graphene-based composites, improved conductivity and hierarchical porosity directly reduce both Rct and diffusion-related impedance contributions.

3 Methodology of systematic review

To assure a comprehensive and unbiased evaluation of the scientific writing concerning graphene and its relatives in electrical power containment, a systematic survey procedure was employed. The procedural structure was created to align with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) directives, with modifications appropriate for materials science investigation.

3.1 Literature exploration approach

The literature scanning was executed across major academic databases (Scopus, Web of Science, ScienceDirect, and PubMed) covering the span from January 2013 to September 2025. This duration was selected to encompass the foremost advancements following the initial broad experimental proofs of graphene-based supercapacitors and accumulators. The search was conducted employing a mix of established keywords and Boolean connectors, comprising:

("graphene" OR "graphene oxide" OR "reduced graphene oxide" OR "doped graphene") AND ("supercapacitor" OR "battery" OR "electrochemical energy storage" OR "hybrid device" OR "anode" OR "cathode").

To uphold uniformity, only scientifically vetted journal pieces were admitted. Conference presentations, patents, and non-vetted accounts were omitted unless they furnished significant procedural novelties or standard data.

3.2 Selection and rejection stipulations

The selection prerequisites were established to pick studies that:

1. Investigate graphene or its derivatives (GO, rGO, doped or hybrid graphene) as primary substances or conductive scaffolds in electrical power containment setups;
2. Present measurable electrochemical figures like specific capability, power/energy magnitude, or cycling durability;
3. Display explicit experimental or computational methods permitting replication;
4. Occur in English-language, scientifically reviewed periodicals.

Research was rejected if they:

1. Focused only on theoretical designs without physical verification;
2. Dealt with irrelevant uses (e.g., catalysis, indicators, water cleansing);
3. Lacked adequate quantitative or procedural specifics.

3.3 Data extraction and categorization

From each chosen publication, the subsequent details were collected:

- Material type and fabrication technique;
- Structural and physical features;
- Electrochemical arrangement (two‑electrode versus three‑electrode setups, electrolyte kind);
- Performance indicators (specific capacitance/capacity, energy and power levels, cycle duration, rate proficiency);
- Mentioned benefits and drawbacks;
- Year of publishing and citation influence.

All information was compiled into a database and later sorted into five primary material groups:

(1) native graphene, (2) graphene oxide, (3) processed graphene oxide, (4) modified graphene, and (5) composite graphene structures.

3.4 PRISMA pathway and assessment of quality

The PRISMA‑guided selection identified 427 initial records, of which 103 were dismissed due to duplication and 211 were filtered out after abstract and title review. A total of 113 complete‑text articles were assessed for eligibility, and 50 were ultimately kept as essential references for this analysis. Quality evaluation was done based on the explicitness of synthesis descriptions, the thoroughness of electrochemical measurement, and the replicability of reported findings. Particular focus was given to investigations providing comparative evaluations or extended usage data, as these more closely assist comprehension of real device functioning.

3.5 Constraints of the review procedure

Despite the organized method, several constraints persist. Reporting bias favoring favorable results, diversities in experimental setups, and the lack of uniformity in reporting performance measures can impede comparisons across studies. Furthermore, the evolving and multidisciplinary nature of graphene investigation suggests that certain very recent or specialized studies may not have been indexed at the moment of review. Nonetheless, the procedure ensures that the review captures an illustrative and crucial overview of the current state of the art.

4 Graphene and its derivatives for supercapacitors

Supercapacitors have garnered substantial interest as supplementary energy storage systems, connecting batteries and conventional capacitors by uniting high power output with extended cycle longevity. Their capability is largely contingent on the selection and engineering of electrode substances, where graphene and its derivatives have shown exceptional promise owing to their electrical conduction, large surface area, and physical robustness [3], [5].

4.1 Pristine graphene and the challenge of restacking

Pristine graphene offers optimal properties for double-layer capacitive storage — a theoretical specific surface area of 2630 $m^2 g^{-1}$ and high electronic mobility — which can facilitate rapid ion adsorption and desorption at the electrode/electrolyte interface. However, its practical use is hampered by the robust π–π interactions between layers, causing restacking of these sheets into graphite-like formations. This phenomenon significantly reduces the available surface area and ion transport pathways, thereby reducing the attainable specific capacitance [12]. The relationship between peak current (i) and scan rate (v) in cyclic voltammetry follows a power-law expression:

$$i = av^b \quad (7)$$

Taking logarithms:

$$\log(i) = \log(a) + b\log(v) \quad (8)$$

The b-value provides mechanistic insight:

- □ ≈ 1 → surface-controlled (capacitive behavior)
- □ ≈ 0.5 → diffusion-controlled process

Graphene-based materials typically exhibit b-values between 0.6 and 1.0, indicating mixed

capacitive and diffusion-controlled contributions. To further separate contributions:

$$i(V) = k_1 v + k_2 v^{1/2} \quad (9)$$

where $k_1 v$ represents capacitive contribution and $k_2 v^{1/2}$ represents diffusion-controlled contribution. This quantitative approach allows objective evaluation of pseudocapacitive enhancement in doped and hybrid graphene systems. Strategies such as physical exfoliation control, incorporation of spacers, and the assembly of three-dimensional (3D) porous structures have been explored to mitigate these effects [9].

4.2 Three-dimensional graphene architecture

Three‑dimensional (3D) graphene architectures — including aerogels, foams, and hydrogels — have emerged as effective remedies to the restacking issue. These interconnected networks offer open macroporous frameworks that enhance ion diffusion and electrolyte infiltration while preserving high electronic conductivity [16]. For instance, freeze‑dried graphene aerogels have recorded capacitances exceeding 250 F g^{-1} along with excellent rate capability and mechanical robustness [17]. Similarly, graphene foams prepared by chemical vapor deposition (CVD) or template‑assisted techniques display remarkable mechanical flexibility and stability across thousands of charge–discharge cycles. The adjustable pore‑size distribution and cross‑linking density enable these materials to act as promising candidates for flexible and wearable supercapacitor electrodes [19].

4.3 Graphene oxide (GO) and reduced graphene oxide (rGO) electrodes

Graphene oxide (GO) and reduced graphene oxide (rGO) are among the most extensively investigated graphene derivatives for supercapacitor applications. GO's plentiful oxygen‑containing groups (hydroxyl, epoxy, and carboxyl) improve dispersibility in aqueous media and facilitate straightforward functionalization with other materials [18]. However, these functional groups disturb the sp^2 network, lowering conductivity. Partial reduction of GO to rGO reestablishes the π‑conjugation while retaining advantageous defects that serve as ion diffusion pathways [5]. rGO‑based electrodes generally display specific capacitances in the span of 150–250 F g^{-1} in aqueous electrolytes, depending on synthesis conditions and degree of reduction [7]. Moreover, flexible rGO films have been effectively integrated into micro‑supercapacitors and wearable devices, showcasing both mechanical durability and outstanding rate performance [9].

4.4 Graphene–metal oxide composites

The combination of graphene with transition metal oxides constitutes one of the most effective approaches to boost pseudocapacitive contributions. Oxides such as MnO_2, RuO_2, and NiO possess large theoretical capacitance but are hindered by poor conductivity and volume expansion during cycling [24]. When integrated with graphene, these drawbacks are alleviated by graphene's conductive framework and mechanical flexibility [17]. For instance, MnO_2 /graphene composites have achieved specific capacitances surpassing 400 F g^{-1} at moderate current densities, while retaining excellent (>90 %) capacity over 5 000 cycles [12], [25]. Similarly, NiO–graphene and RuO_2 –graphene hybrids exhibit high power density and improved ionic accessibility, showing potential for both aqueous and solid‑state configurations [16]. These hybrid structures derive benefit from synergistic effects, integrating electric double‑layer storage with faradaic redox processes, and thus delivering higher energy densities without compromising cycling stability.

4.5 Graphene–conducting polymer composites

Another promising pathway involves merging graphene with conductive polymers such as polyaniline (PANI) and polypyrrole (PPy) [26]. These polymers offer pseudocapacitance via reversible redox processes, while graphene supplies a pliable, conductive structure that lessens polymer breakdown and boosts charge conveyance [5]. PANI/graphene composites, for instance, have shown specific capacitances as high as 600 F g^{-1} and remarkable cyclic longevity, retaining above 85% of initial capacity subsequent to 5,000 cycles [7]. Similarly, PPy/graphene setups demonstrate enhanced rate capacity owing to the effective spreading of active sites across the graphene foundation [9]. The mechanical toughness and suppleness of these composites render them prime choices for forthcoming flexible and wearable power storage units.

4.6 Typical performance and practical applications

Broadly, graphene‑based supercapacitors exhibit specific capacitances within the range of 150–600 F g^{-1}, energy levels between 10–40 Wh kg^{-1},

and power levels exceeding 10 kW kg^{-1}, contingent on the material configuration and electrolyte [17]. Three‐dimensional and composite systems present particularly steady operation, frequently preserving more than 90 % of their initial capacitance after 10 000 cycles. Furthermore, adding graphene electrodes onto flexible supports has cleared the path for portable supercapacitors, microelectronic power sources, and energy‐gathering systems that combine mechanical pliability with rapid charge–discharge aptitude [19]. In sum, the incorporation of graphene and its variations into supercapacitor anodes has significantly propelled the domain of high‐efficiency energy retention, marking an important advance toward adaptable, light, and robust devices capable of satisfying future needs in portable and wearable electronics.

To present a comparative overview of the electrochemical results of graphene and its variations in supercapacitor uses, Table 2 details the main structural and functional aspects of each material kind. The assessment covers pristine graphene, its oxidized and restored forms, alongside hybrid structures that contain metal oxides or conductive polymers. The detailed metrics — such as specific capacitance, cycling robustness, and typical uses — arise from representative laboratory discoveries in the documentation [3], [5], [7], [17]. This structure assists a clearer insight into how diverse chemical and surface modifications impact the total electrochemical function and real-world suitability of graphene‐based anodes.

Table 2. Comparative summary of graphene-based materials and their electrochemical performance in supercapacitor applications. Data adapted from Xu et al. (2013); Li et al. (2019); Tiwari et al. (2020); Ahmad et al. (2023); Devendran & Nagai (2023); Pathak et al. (2025)

Material Type	**Key Features**	**Specific Capacitance (F/g)**	**Cycle Stability (%)**	**Typical Applications**
Pristine Graphene	High surface area and conductivity; limited by sheet restacking	80–150	~85% after 5000 cycles	Basic EDLC electrodes; limited energy density
3D Graphene (Aerogel, Foam, Hydrogel)	Porous 3D networks enhance ion diffusion and electrolyte access	200–300	≥90% after 5000 cycles	Flexible and wearable devices; high-rate capability
Graphene Oxide (GO)	High functionalization; good dispersion; poor conductivity	100–200	~80% after 3000 cycles	Composite precursors; aqueous supercapacitors
Reduced Graphene Oxide (rGO)	Restored conductivity; defect-assisted ion pathways	150–250	≥90% after 5000 cycles	Micro-supercapacitors; flexible films
Graphene + Metal Oxides (MnO_2, NiO, RuO_2)	Synergistic pseudocapacitance and high energy density	300–450	90–95% after 5000 cycles	Hybrid pseudocapacitors; high power/energy density
Graphene + Conducting Polymers (PANI, PPy)	Enhanced redox activity and flexibility from polymer integration	400–600	85–90% after 5000 cycles	Flexible supercapacitors; wearable electronics

As illustrated in Table 2, pure graphene, despite its remarkable intrinsic conductivity and theoretical surface area, offers relatively modest capacitance values due to the unavoidable restacking of its nanosheets. Three-dimensional graphene frameworks, like aerogels and foams, address this problem by forming linked porous systems that considerably boost electrolyte access and ion movement, attaining specific capacitances generally near 200–300 F g^{-1} with superb cycling endurance [27]. Graphene oxide (GO) and reduced graphene oxide (rGO) constitute adaptable intermediary structures. GO offers superb dispersal and functionalization capability, rendering it helpful as a starting material for composites, though its electrical conductance stays low. rGO partly restores electrical conductivity while retaining structural flaws that encourage charge buildup, yielding steady capacitances spanning 150–250 F g^{-1}. In combined materials, combining graphene with metal oxides (e.g., MnO_2 , RuO_2 , NiO) or conductive polymers (PANI, PPy) leads to notable complementary benefits. These assemblies display substantially greater capacitances—frequently exceeding 400 F g^{-1}—owing to the simultaneous presence of double‐layer and faradaic charge‐storage

processes. Furthermore, graphene–polymer assemblies display outstanding pliability and structural resilience, making them particularly attractive for portable and adaptable energy‑storage units. In summary, the findings emphasize a continuous enhancement in both energy and power capability as functional intricacy increases, with hybrid graphene‑based architectures currently representing the most encouraging path for future supercapacitors.

5 Graphene and derivatives for batteries

The integration of graphene and its analogs into battery electrodes has arisen as one of the most promising avenues to boost electrochemical performance regarding conductivity, capacity, rate capability, and lasting cycling stability. Due to its two-dimensional structure, robust mechanical strength, and superb electron mobility, graphene can function both as a reactive substance and as a conductive framework that supports other electrochemically active components [3], [5]. These attributes make it a versatile component across various battery systems, including lithium‑ion (Li‑ion), sodium‑ion (Na‑ion), zinc‑ion (Zn‑ion), and hybrid metal‑ion batteries.

5.1 Graphene and derivatives in Lithium-Ion Batteries (Li-ion)

Lithium‑ion batteries (LIBs) persist as the primary technology in portable and vehicle applications, although they encounter hurdles such as restricted energy volume, structural degradation, and unstable solid‑electrolyte junctures throughout extended operation. Graphene has been frequently utilized to alleviate these issues, either as a very conductive additive or as a backing structure for reactive materials [17]. Graphene-based anodes improve charge conveyance routes and ease the volumetric expansion of alloy-type substances such as silicon (Si) and tin (Sn). For instance, Si/graphene composites display markedly greater reversible capacities (up to 1500 $mAh\,g^{-1}$) and dependable cycling through hundreds of charge–discharge repetitions [16]. Reduced graphene oxide (rGO) likewise assists in forming conductive webs that lessen fragmentation and foster consistent lithium‑ion migration (Tiwari et al., 2020). At the cathode terminus, graphene functions as an effective conductive covering or structure for materials like $LiFePO_4$, $LiCoO_2$, and $LiMn_2O_4$, lifting their rate capability and minimizing structural breakdown during high-rate cycling. As an illustration, $LiFePO_4$ /graphene composites demonstrate augmented conductivity and yield specific capacities surpassing 160 $mAh\,g^{-1}$ at 1C, with excellent retention after 500 cycles [9].

5.2 Graphene and derivatives in sodium- and zinc-ion batteries

Beyond Li‑ion systems, the exploration of sodium‑ion (Na‑ion) and zinc‑ion (Zn‑ion) batteries has increased because of their reduced cost and resource abundance. However, their greater ionic radii (Na^+ , Zn^{2+}) pose challenges in diffusion kinetics as well as electrode stability. Graphene's flexibility, high surface area, and defect‑rich structures make it especially well‑suited to accommodate these ions [12]. In Na‑ion batteries, nitrogen‑doped graphene and rGO have shown improved sodium storage capabilities, owing to their improved binding energy with Na^+ and a greater number of active sites. Recorded capacities for these materials range between 250–400 $mAh\,g^{-1}$, with high reversibility [18]. For aqueous Zn‑ion systems, graphene oxide and hybrid composites have demonstrated outstanding stability and rate performance. $ZnMn_2O_4$ /graphene composites, for example, deliver capacities around 300 $mAh\,g^{-1}$ and retain over 90 % of the initial performance after 1000 cycles, thanks to graphene's capacity to prevent dendritic growth and enhance electronic conductivity [19].

5.3 Graphene–metal oxide and graphene–sulfide composites

The combination of graphene with transition‑metal oxides and sulfides (e.g., Fe_3O_4 , Co_3O_4 , MoS_2 , NiS_2) has yielded notable progress in electrode architecture. These composites merge the high theoretical capacities of the redox‑active components with the conductivity and flexibility of graphene sheets [17], [16]. Graphene–Fe_3O_4 composites have demonstrated reversible capacities exceeding 900 $mAh\,g^{-1}$, while preserving excellent rate capability owing to the swift electron and ion transport through graphene networks [7]. Likewise, MoS_2 /graphene heterostructures display stratified structures that enhance interfacial charge transfer and mitigate volume variation during cycling, attaining high energy densities in both Li‑ion and Na‑ion configurations [9].

5.4 Graphene–polymer and graphene–carbon hybrid frameworks

Conductive polymers such as polyaniline (PANI) and polypyrrole (PPy) have also been successfully integrated into graphene-based electrodes for power cells, acting as ionic-conductive links or adaptable active elements [28]. These mixtures promote superior interfacial contact and offer pseudocapacitive charge containment, leading to quicker dynamics and boosted rate capability [5]. Furthermore, hybrid compositions joining graphene with carbon nanotubes (CNTs) or carbon nanofibers (CNFs) create layered conductive meshes with significant void volume. Such structures lessen clumping and encourage ion movement in multiple directions [29]. As an illustration, graphene/CNT blends in Li-ion power cells attain consistent specific charge levels near 800 mAh g^{-1} and sustain >90% charge retention across 500 cycles [5].

5.5 Typical results and outlook

In summation, graphene and its variants have substantially boosted the functioning of present battery systems. In Li-ion power cells, graphene compositions generally reach specific charge levels of 400–1500 mAh g^{-1} dependent on the setup, whereas in Na-ion and Zn-ion setups, they offer high reversibility and better security [18], [19]. Their excellent electronic conductivity and physical resilience permit remarkable cycling durability, frequently exceeding 90% charge retention over several hundred to a thousand cycles. Despite these merits, hurdles remain concerning mass manufacturing, interface steadiness, and the balance between energy density by weight and by volume. Upcoming investigations will likely concentrate on logical material design, control of structure across scales, and environmentally friendly creation methods to yield affordable, high-output graphene-based electrodes suitable for advanced rechargeable power cells and combined energy storage platforms.

To detail the electrochemical response of graphene-based substances in diverse power cell frameworks, Table 3 offers a comparative overview demonstrating their structural roles, capacities, cycling longevity, and main advantages.

Table 3. Comparative summary of graphene-based materials in different battery systems. Data adapted from Xu et al. (2013); Li et al. (2019); Tiwari et al. (2020); Devendran & Nagai (2023); Du et al. (2023); Ahmad et al. (2023); Kausar et al. (2023); Pathak et al. (2025)

System	Material Type	Function	Specific Capacity (mAh g^{-1})	Stability	Highlights / Advantages
Li-ion Battery	Graphene / rGO / Graphene–Si or Sn composites	Conductive framework; volume expansion buffering; enhanced Li^+ diffusion	400–1500	>90% after 500 cycles	Improved electrical conductivity; mitigated pulverization; stable SEI formation
Li-ion Battery (Cathodes)	$LiFePO_4$ / Graphene, $LiMn_2O_4$ /Graphene	Conductive coating; improved ion transport	140–170	>95% after 500 cycles	Enhanced rate capability and structural stability
Na-ion Battery	N-doped Graphene, rGO	Active host for Na^+; defect-mediated storage	250–400	~90% after 1000 cycles	Increased active sites and binding energy for Na^+; fast kinetics
Zn-ion Battery (Aqueous)	GO / Graphene–MnO_2 or $ZnMn_2O_4$ composites	Prevent dendritic growth; enhance ionic conductivity	250–350	>90% after 1000 cycles	Excellent performance rate and mechanical stability in aqueous electrolytes
Hybrid Metal-Ion Batte	Graphene–MoS_2, Graphene–Fe_3O_4, Graphene–	Synergistic redox behavior; high-capacity	600–1000	85–95% after 800 cycl	Combined faradaic and capacit

ries	NiS_2 composites	retention		es	ive charge storage ; high energy density
Flexible / Polymer-Based Batteries	Graphene–PANI / Graphene–PPy composites	Flexible, conductive, and pseudocapacitive components	200–500	>85 % after 1000 cycles	Enhanced mechanical flexibility and rapid charge–discharge response

Table 3. summarizes the many functions of graphene and its derivatives in various battery systems, from conductive frameworks and structural stabilizers to active charge-storage medium. The ability of graphene–silicon and graphene–tin composites to buffer volumetric expansion and maintain high specific capacities exceeding 1000 mAh g^{-1} makes them particularly noteworthy in lithium-ion batteries [30]. In the same way, graphene coatings on cathode materials like $LiFePO_4$ and $LiMn_2O_4$ improve electron routes and stop mechanical deterioration over time. Owing to their numerous defect locations and strong Na^+ uptake, nitrogen-doped and reduced graphene oxide anodes in sodium-ion cells display substantial sodium storage quantities (250–400 mAh g^{-1}) and excellent recoverability. With above 90% capacity maintenance following 1000 cycles, graphene-based architectures successfully curb dendritic growth and electrolyte breakdown, which often restrict efficacy in zinc-ion setups. Thanks to their swift interfacial charge movement and combined redox action, mixed constructs like MoS_2 /graphene and Fe_3O_4 /graphene demonstrate outstanding functionality, bridging the divide between capacitive and battery-style operation. Lastly, graphene–polymer mixtures, such as PANI and PPy complexes, marry structural resilience with rapid charge–discharge speeds to unlock fresh prospects for adaptable and wearable power storage. In total, the research illustrates graphene's flexibility as an electrochemical and physical scaffold that can boost energy and power outputs while sustaining extended cycling steadiness across diverse battery types

6. Graphene-Based Design Approaches for Electrochemical Energy Storage: Prospects and Constraints

The creation of future electrochemical energy storage apparatus increasingly depends on the precise fabrication of graphene-derived substances [31]. Through structural alteration, heteroatom incorporation, and blending with compatible substances, researchers have achieved notable advances in energy and power densities, charge–discharge velocity, and physical robustness [3], [7]. Nevertheless, despite these improvements, several primary challenges persist that impede broad adoption. This section provides a vital review of the most relevant design techniques, emphasizing their influence on performance and practical limitations.

6.1 Structural engineering and morphology control

One of the most effective design strategies for enhancing the electrochemical performance of graphene-based materials involves governing their structure at multiple scales. Pristine graphene tends to restack due to strong van der Waals forces, leading to limited ion accessibility and reduced capacitance. To overcome this concern, various three-dimensional (3D) architectures — including aerogels, foams, and hydrogels — have been developed to introduce hierarchical porosity and facilitate swift ion diffusion [9], [16]. These 3D networks retain high electrical conductivity while providing continuous electrolyte pathways, resulting in superior electrochemical kinetics. For example, freeze-dried graphene aerogels can yield capacitances exceeding 250 F g^{-1} with excellent rate capability, demonstrating how structural openness directly translates into functional performance [17]. Moreover, surface texturing and pore-size tuning have appeared as critical design parameters for improving both gravimetric and volumetric energy density. The introduction of meso- and macropores enhances ion transport, while micropores contribute to charge accumulation. Advanced synthesis methods, such as chemical vapor deposition (CVD) and template-assisted self-assembly, allow precise control over these parameters [18], [32]. Nonetheless, reproducibility and scalability of these complex architectures remain ongoing challenges.

6.2 Heteroatom doping and chemical functionalization

Graphene's chemical alteration via heteroatom incorporation (like nitrogen, boron, sulfur, phosphorus) introduces additional electroactive sites,

adjusts electron distribution, and improves pseudocapacitive performance [12], [19]. For instance, nitrogen-doped graphene improves wettability and charge movement effectiveness, whereas boron incorporation boosts hole concentration and responsiveness to redox reactions [5], [33]. Doping not only strengthens the electrochemical reaction but also stabilizes the electrode/electrolyte interface, which is crucial for sustaining capacity over extended cycling [34]. Graphene doped with twin heteroatoms (e.g., N–S or N–P) has exhibited combined effects, reaching specific capacitances up to 600 F g^{-1} in hybrid setups [16]. Nevertheless, accurate management over dopant quantity and configuration continues to be difficult, frequently resulting in inconsistent material characteristics. Furthermore, the synthesis methods — normally involving elevated temperatures and hazardous raw materials — present environmental and economic considerations [18].

6.3 Hybridization with metal oxides, sulfides, and polymers

The combination of graphene with transition metal oxides (MnO_2, NiO, RuO_2), sulfides (MoS_2, NiS_2), and conductive polymers (PANI, PPy) has proven highly beneficial in attaining synergistic charge-storage mechanisms [17], [7]. In such hybrid assemblies, graphene functions as a conductive framework that lessens the inherent disadvantages of active materials, such as low conductivity or mechanical fragility. For instance, MnO_2 /graphene and PANI/graphene composites merge double-layer capacitance with faradaic redox activity, leading to high energy densities (30–45 Wh kg^{-1}) and extended cycling persistence (>90% retention after 5000 cycles) [5], [9]. Likewise, MoS_2 /graphene and Fe_3O_4 /graphene composites show superior lithium or sodium storage abilities due to proficient interfacial charge movement and lessening of volume changes during cycling [16]. In spite of these merits, the preparation of uniform hybrids stays difficult, as uncontrolled clustering or uneven spreading of the secondary phase might result in poor replicability and limited scalability.

6.4 Interface engineering and defect control

An additional decisive design approach involves engineering the electrode/electrolyte boundary to optimize ion accessibility and lessen charge-transfer impedance. Flaws, boundary locations, and functional moieties on graphene serve as reactive sites for ion uptake and oxidation-reduction processes [3]. While intermediate defect densities can enhance electrochemical sensitivity, excessive anomalies diminish conductance and structural integrity [17]. Advanced interface engineering strategies, including atomic layer deposition (ALD) and surface shielding, are being employed to reconcile these effects. For example, surface covering with ultrathin oxide films can curb side reactions and stabilize the solid–electrolyte interphase (SEI) in graphene-based anodes [12]. Moreover, linking in situ spectroscopic and computational assessments has allowed a deeper comprehension of how defect chemistry influences ion diffusion kinetics and electrode resilience [7].

6.5 Sustainable and scalable synthesis approaches

Although graphene presents outstanding electrochemical traits, its broad deployment hinges upon the capacity to manufacture it economically, reliably, and durably. Standard procedures like CVD and chemical diminishing of graphene oxide create superior substances but necessitate hazardous substances or substantial power usage [18]. To tackle these problems, current investigation has centered on eco-friendly preparation techniques — encompassing biomass-sourced graphene, electrical abrasion, and hydrothermal pathways — that lessen ecological impacts while preserving comparable efficacy [16], [19]. Even so, ensuring uniformity in grade throughout big quantities stays a constraint. Furthermore, regulating variables like particle dimension, imperfection concentration, and layer evenness is vital for attaining foretellable electrochemical responses [17]. Expandable fabrication methods incorporating roll-to-roll covering, stamping, or inkjet placement demonstrate potential for high-volume creation of graphene components for adaptable and portable power containment setups [9].

6.6 Opportunities and limitations

Collectively, the design approaches mentioned above showcase the adaptability and adjustability of graphene-based substances. The blend of superior electrical conductivity, structural strength, and chemical modifiability renders graphene a perfect foundation for building high-efficiency electrodes for both supercapacitors and batteries [5], [35].

Prospects involve:

- The potential to incorporate graphene-based composites into versatile devices merging energy storage with sensing or catalysis;
- The creation of pliable and clear electrodes for portable and microelectronic assemblies;

- The employment of eco-friendly and scalable manufacturing pathways to connect laboratory results with commercial use.

Nevertheless, constraints persist significantly. These encompass:

- Incomplete comprehension of the relationship among structure, flaws, and charge movements across various size scales;
- Restricted command over the consistency and replicability of modified or combined materials;
- Expense and energy demands of broad manufacturing;
- Ecological worries linked to solvent usage and chemical starting materials.

Resolving these challenges necessitates a multidisciplinary method uniting materials study, electrochemistry, and process planning. Upcoming investigation must emphasize precise structure–property connections, real-time examination, and sustainability-focused production techniques to completely realize graphene's promise in electrochemical energy storage systems [18], [19].

6.7 Simulation and Simplified Modeling of Graphene-Based Electrodes

Numerical modeling provides additional insight into the electrochemical behavior of graphene-derived materials. Based on Eq. (5), diffusion-limited performance scales with L^2/D. In 3D porous graphene, reduced diffusion length and enhanced effective diffusion coefficients improve high-rate operation. Equivalent circuit simulations using Rs–Rct–Cdl–Zw models reproduce impedance spectra and allow extraction of charge-transfer resistance and diffusion parameters. Lower Rct values in graphene–metal oxide composites confirm improved interfacial kinetics. Cycling degradation can be framed using Coulombic efficiency (Eq. 1). Progressive deviation from ideal $\eta = 100\%$ indicates parasitic reactions, SEI thickening, or structural collapse. These simplified models provide a quantitative bridge between structural design and electrochemical performance.

7 Advanced applications of graphene and its derivatives in electrochemical energy storage

The swift advancement in the structure and preparation of graphene-based materials has unlocked novel avenues for their deployment in cutting-edge electrochemical energy retention setups. Beyond typical supercapacitors and batteries, graphene's singular blend of electrical, mechanical, and chemical attributes permits its incorporation into pliable, wearable, and multipurpose gadgets that connect the divide between energy retention, energy gathering, and detection [9], [18], [36]. This segment details the most promising paths in the utilization of graphene and its derivatives, concentrating on flexible and wearable energy retention, combined systems, micro-supercapacitors, and extensive grid and transport technologies.

7.1 Flexible and wearable energy storage devices

One of the most dynamic areas of research involves the creation of flexible and wearable supercapacitors and batteries, where graphene assumes a dual role as both an electroactive element and a flexible conductive base [17], [37]. The outstanding mechanical pliability and break resistance of graphene sheets permit the construction of bendable and stretchable supports without diminishing electrochemical capability [5]. Graphene-based films, hydrogels, individual units, and textile-integrated composites have demonstrated the ability to retain above 90% charge capacity even through cycles of repeated flexing or turning [12]. For example, rGO/PANI nanocomposites placed onto carbon textiles yield characteristic charges surpassing 500 F g^{-1} while keeping steady operation under 180° flexion. Likewise, flexible Li-ion power cells featuring graphene–CNT composite supports merge high power output with mechanical toughness, rendering them perfect for emerging smart textile and portable electronic applications [9]. Also graphene based bismuth–niobium nanocomposites [38] and based mixed metal sulphide nanocomposite [39] was studies to enhance supercapacitor performance. Still, difficulties remain regarding sealing, prolonged endurance under physical strain, and combining with flexible charge carriers. Progress on solid-state or gel polymer electrolytes suitable for graphene supports constitutes a vital move toward entirely adaptable and secure wearable power setups [7], [40].

7.2 Micro- and on-chip energy storage devices

The downscaling of energy storage elements is crucial for energizing microelectronic gadgets, MEMS sensors, and IoT setups. Graphene's large surface area and electrical conductance render it a top choice for micro-supercapacitors (MSCs), where the electrode structure is usually established via laser scribing, inkjet printing, or photolithographic methods [3]. Laser-induced graphene (LIG), fabricated directly onto polymer surfaces, has attained significant focus due to its

straightforwardness and scalability. LIG-based MSCs attain surface capacitances as high as 10 mF cm^{-2} with swift charge–discharge speeds and lasting durability (>10,000 cycles) [17]. Additionally, rGO and modified graphene inks allow for patterned and layered microelectrodes, providing an equilibrium between energy and power densities appropriate for incorporation into self-governing sensors or bioelectronic setups [16]. These apparatuses show the capability to function beneath slight voltages (<2 V), providing quick charging and suitability with pliable substrates—vital attributes for the coming era of low-power electronics. Nevertheless, the compromise between size reduction and overall energy storage persists as a restricting aspect, stressing the necessity for further progress in material formulation and device structure [19].

7.3 Hybrid and multifunctional energy systems

Graphene's tunable chemistry also permits its utilization in hybrid apparatuses that merge the swift charge–discharge attributes of supercapacitors with the substantial energy concentration of batteries [5], [9]. These so-called battery–supercapacitor hybrids (BSHs) utilize graphene as a conductive connection between capacitive and faradaic terminals [41], [42], [43]. For instance, asymmetric setups comprising graphene–MnO_2 as the positive terminal and rGO as the negative terminal can attain energy densities of 40–60 Wh kg^{-1} at power densities surpassing 5 kW kg^{-1} [7]. Likewise, graphene–Fe_3O_4 /$LiMn_2O_4$ hybrid structures have demonstrated superb rate performance and cycling longevity, suggesting their promise for grid-scale or automotive storage uses [17]. Apart from energy retention, multipurpose frameworks incorporating graphene-based terminals with detectors, solar cells, or piezoelectric scavengers are becoming popular. These self-powered setups can concurrently maintain and create power, opening avenues for self-governing and intelligent electronic gadgets [18], [16].

7.4 Large-scale and grid-oriented energy applications

While much exploration on graphene-based materials has centered on small-scale apparatus, their incorporation into extensive and grid-linked setups is starting to gain notice. Graphene can boost both electrode permanence and charge-transfer effectiveness in flow batteries and metal–air batteries, where prolonged endurance and chemical resilience are vital [12], [44]. In zinc–air and lithium–sulfur batteries, graphene-based cathodes augment sulfur usage and curb polysulfide shuttling, yielding consistent operation across numerous cycles [16]. Furthermore, graphene-covered partitions have demonstrated a lowering of internal resistance and an improvement in security, especially in high-voltage setups [17]. At the grid level, mixed graphene–carbon composites are also being evaluated for high-power supercapacitor arrays intended to stabilize renewable energy fluctuations. These mechanisms can offer rapid reaction speeds, great effectiveness, and longer functional lifetimes relative to standard carbon electrodes [19], [45]. Nonetheless, expense, scalability, and consistency remain crucial hurdles for industrial deployment.

7.5 Future outlook

The incorporation of graphene into varied energy storage frameworks signifies a new phase toward multifunctional, top-tier, and environmentally sound apparatuses. Pliable and composite graphene-based setups are set to transform portable electronics, electrical transport, and intelligent network systems. The ongoing merging of nanomaterial refinement, printing techniques, and eco-friendly production modes will more quickly advance the shift from lab-scale achievements to market-ready answers [16], [18]. Nevertheless, broad acceptance necessitates resolving ongoing challenges:

- the premium price and inconsistency of graphene creation
- the normalization of evaluation guidelines to permit comparative review of efficacy metrics
- the ecological effect linked to massive-scale creation.

Surmounting these hurdles will depend on the collaboration between substance formulation, apparatus assembly, and overall system refinement to achieve the complete capability of graphene in forthcoming electrochemical power conservation methods [17], [19].

8 Challenges and current limitations

Despite notable advancement in the creation and employment of graphene-based materials for electrochemical energy storage, several technical, financial, and ecological hurdles still impede their broad application. These difficulties relate to the inherent characteristics of graphene, the intricacy of its derivatives, and the scalability of the methods needed to incorporate them into industrially significant devices. This segment critically reviews the main constraints impacting performance, consistency, and market potential.

8.1 Scalability and production costs

A principal hurdle in the real-world application of graphene-based electrodes involves the scalability of manufacturing while preserving material excellence and consistency. Standard production techniques like chemical vapor deposition (CVD) and the Hummers oxidation–reduction procedure yield premium graphene but necessitate costly starting materials, hazardous reagents, and energy-demanding environments [5], [16]. Different routes, encompassing electrochemical exfoliation, mechanochemical creation, and graphene derived from biomass, have been investigated to lessen expense and ecological footprint. Nevertheless, these approaches frequently result in substances with uneven thickness, shifting defect concentration, or unregulated functional group prevalence, causing erratic electrochemical performance [17]. The absence of established guidelines for assessing layer count, purity, and conductivity further impedes assessment across studies. From a financial viewpoint, the price per kilogram of superior graphene stays substantially greater than that of common carbon substances (e.g., activated carbon or carbon nanotubes), restricting its deployment to specialized or high-worth uses [18], [46].

8.2 Structural stability and restacking

The tendency of graphene sheets to restack due to van der Waals forces keeps limiting the available surface area and ion movement within the electrode structure [3]. This structural collapse causes a decrease in capacitance and energy metrics, particularly during prolonged cycling or substantial mass loading. While the creation of 3D porous designs (aerogels, foams, and hydrogels) and mixed frameworks utilizing spacers like metal oxides or plastics has eased this issue, preserving structural soundness across numerous charge–discharge repetitions stays a constant difficulty [9], [7]. Moreover, the compromise between void space and capacity per volume hinders device refinement: greater porosity boosts ion flow but lowers the density of the functional material.

8.3 Interface instability and side reactions

The electrode/electrolyte boundary holds a vital place in establishing the effectiveness and lifespan of electrochemical setups. Graphene's notable reactivity, especially when reduced, can result in unwanted secondary reactions such as electrolyte breakdown, gas generation, and the creation of shaky solid–electrolyte interphases (SEI) in power storage assemblies [12], [17]. These problems are exacerbated during high potential or harsh thermal conditions [47], [48]. Interface adjustment methods—like surface deactivation, impurity addition, and covering with extremely thin oxide sheets—can lessen these impacts, but perfecting the chemical harmony between graphene and electrolytes stays unsolved [5], [19]. Furthermore, in composite materials featuring metal oxides or sulfides, size change and structural misalignment during redox processes can cause physical strain and separation, eventually causing performance decline [16].

8.4 Environmental and safety concerns

The ecological viability of graphene manufacturing and discard has surfaced as a principal worry. The standard Hummers procedure, for example, creates substantial volumes of acidic refuse containing weighty elements and oxidizers, presenting hazards to both individual well-being and the surroundings [18]. Although eco-friendly synthesis approaches, encompassing plant-extract mitigation and electrolytic peeling, are being advanced, their large-scale applicability stays constrained. Moreover, the poisonous impact of graphene bits is not yet completely known; initial research indicates possible dangers associated with breathing, dermal contact, and prolonged environmental presence [16]. Regarding safety, graphene's high electric conductance and propensity to react necessitate stringent management procedures, particularly when handling powders or constructing electrodes. Thorough life cycle analyses (LCA) are thus vital to gauge the genuine endurance of graphene-based innovations [17].

8.5 Lack of standardization and reproducibility

The lack of conventional testing and reporting guidelines represents one of the chief impediments to coherent comparison among research [7], [9]. Differences in electrode making, conducting fluid makeup, and evaluation settings can cause variances surpassing 50% in cited capacitance or capacity figures. Likewise, the diversity of gauging metrics (e.g., F g^{-1} versus mAh g^{-1}, or Wh kg^{-1} versus Wh L^{-1}) and variations in scaling techniques (dependent on overall weight versus active substance mass) complicate inter-study benchmarking. Instituting collective criteria—much like those created for lithium-ion cells—is crucial to guarantee replicability and hasten commercial adoption [18].

8.6 Economic viability and integration challenges

While graphene enhances the electrochemical capability of diverse storage systems, the cost-to-efficiency balance is still unfavorable for widespread commercial uses. Incorporating graphene electrodes into current manufacturing processes, particularly in the vehicle and power sectors, necessitates compatibility with roll-to-roll or slurry-style application methods [19]. Moreover, expanding electrode size presents novel difficulties concerning bonding, consistency, and physical resilience. For extensive surface area units, guaranteeing consistent film depth and reducing flaws like fissures or gaps is technically challenging [17]. The total unit expense is still largely determined by the expense of graphene starting materials and manufacturing stages, highlighting the requirement for affordable, high-output creation methods and sustainable lifecycle practices.

8.7 Summary of key limitations

To offer a brief summary of the principal obstacles currently impeding the practical implementation of graphene-based materials in electrochemical energy storage, Table 4 encapsulates the main difficulties noted in recent publications. These constraints involve structural, chemical, ecological, and financial facets that jointly affect device effectiveness and potential for expansion. Particularly, the table details how elements such as manufacturing scalability, restacking of the graphene sheets, surface instability, and environmental consequence contribute to diminished energy utilization, constrained lifespan, and variable consistency across investigations [5], [17], [16]. The lack of standardized evaluation and trial procedures further complicates the mutual comparison of results and postpones the conversion of research findings into commercial uses [7], [18].

Table 4. summary of key limitations of graphene use

Limitation	Description	Impact on performance
Scalability	High cost and complexity of synthesis methods	Restricts mass production
Restacking	Reduced accessible surface area and ion diffusion	Lower capacitance and power density
Interface instability	Side reactions, SEI formation, and delamination	Poor cycling stability
Environmental issues	Toxic reagents and waste management	Safety and sustainability concerns
Lack of standardization	Inconsistent testing methodologies	Non-reproducible results
Economic viability	High material cost and integration barriers	Limited commercialization

The comparative summary shown in Table 4 reveals the complex character of the obstacles presently hindering the broad utilization of graphene-derived substances in electrochemical energy saving. Amidst these, scalability and manufacturing expense persist as the most vital impediments, since superior-grade graphene creation still rests upon costly starting materials and exhaustive procedures. Although nascent sustainable and electrolytic shedding methods proffer a greener path, they frequently deliver substances featuring varied structures and unequal electrochemical functioning [18], [16]. The problem of re-stacking, intrinsic to the two-dimensional quality of graphene, keeps restricting accessible surface expanse and ion conveyance, directly diminishing energy and power outputs. This constraint has prompted the design of three-dimensional and combined frameworks, though these bring forth novel hurdles regarding replicability and volumetric density [9]. Interface volatility and secondary actions—especially in high-voltage or watery setups—constitute another primary worry. Uncontrolled arrangement of interphases, electrolyte breakdown, and gas emergence result in meager cycle durability and capacity decline [17]. While interface configuration and impurity strategies have afforded partial lessening, guaranteeing enduring electrochemical synergy stays difficult. From a hazard and ecological viewpoint, the utilization of dangerous compounds and the generation of poisonous byproducts during standard creation sequences raise considerable sustainability questions. Life cycle appraisals (LCAs) indicate that the carbon impact of graphene output is still considerable versus conventional carbons, underscoring the necessity for nature-friendly and closed-system processing [5]. Equally important is the absence of uniformity in appraisal methodologies, which weakens data correlation and repeatability. Adopting standardized performance measures and disclosure norms—much like those confirmed for lithium-ion battery investigation—would be helpful in hastening commercial verification [7]. Lastly, the fiscal viability of graphene-based instruments hinges on finding equilibrium between substance effectiveness and expense-effectiveness. Incorporating graphene

into vast manufacturing streams necessitates suitability with existing roll-to-roll covering and printing methods. Until these difficulties are addressed, the shift from laboratory-scale achievement to business-scale generation will persist a significant undertaking. In short, Table 4 illuminates that while graphene's capacity for high-output energy saving is certain, harnessing its technological and commercial potential will rely upon interdisciplinary ingenuity—fusing material knowledge, sustainable design, and industrial operation refinement.

8.8 Outlook

In conclusion, while graphene has revolutionized the domain of electrochemical energy storage, unlocking its complete capability necessitates tackling these multifaceted hurdles via aligned scientific and commercial endeavors. The prospect of graphene-based storage assemblies hinges upon:

1. The devising of inexpensive, scalable, and benign synthesis pathways;
2. The incorporation of simulation tools and AI to conceive flaw-refined and interface-structured substances;
3. The establishment of uniform performance standards to guarantee replicability and industrial suitability;
4. The progression of reclamation and final-use plans consistent with ecological advancement targets.

Through conquering these obstacles, graphene and its analogues might transition from academic novelties to foundational components for premium, lasting, and circular electrochemical energy storage methods [16], [19].

9 Conclusions and future perspectives

Over the past ten years, graphene and its variations have surfaced as prime substances in the advancement of electrochemical energy conservation systems. Their superb blend of high electrical conductivity, large surface expanse, mechanical pliability, and chemical tunability has reshaped the performance ceiling of both supercapacitors and rechargeable batteries. Via methodical examination of the literature, this survey has emphasized the headway attained in the conception, fabrication, and utilization of graphene-based substances while rigorously assessing their obstacles and constraints. In supercapacitor setups, pure and reduced graphene oxide (rGO) have shown remarkable power densities and cycling permanence, whereas hybrid composites with metal oxides (MnO_2 , NiO, RuO_2) and conducting polymers (PANI, PPy) have successfully connected the divide between electric double-layer and pseudocapacitive processes [5], [7]. The inclusion of 3D graphene frameworks such as aerogels, foams, and hydrogels has further bolstered ion transport dynamics and mechanical soundness, permitting their incorporation into pliable and wearable energy gadgets [9], [49]. Within the scope of battery technologies, graphene's conductive and structural attributes have notably boosted lithium-, sodium-, and zinc-ion arrangements. Graphene–metal oxide and graphene–sulfide composites have attained high specific capacities and steady cycling through efficient charge movement and volume-change adaptation [17], [16]. Furthermore, hybrid constructions incorporating doped or polymeric graphene have broadened the range of multifunctional, adaptable, and high-energy-density terminals. The survey likewise pinpointed key design tactics underpinning these accomplishments — specifically morphology control, heteroatom doping, interface engineering, and hybridization — as the most powerful ways of augmenting electrochemical performance [12], [19]. Nevertheless, the domain still contends with ongoing limitations: scalability of output, restacking issues, interfacial fragility, ecological worries, and the lack of standardized assessment procedures [18]. These difficulties jointly impede the shift from laboratory-scale success to industrial-scale deployment. Moving forward, subsequent inquiry ought to concentrate on several strategic paths:

1. Scalable and sustainable synthesis routes — Evolution of eco-friendly and cost-effective production techniques, such as biomass-derived graphene and electrochemical exfoliation, to substitute energy-intensive or chemically perilous procedures.
2. Integrated multi-material architectures — Rational layout of hybrid systems merging graphene with novel two-dimensional materials (e.g., MXenes, boron nitride, transition metal dichalcogenides) to realize synergistic enhancements in energy and power density.
3. Advanced characterization and modeling — Employing in situ and operando spectroscopy, alongside computational simulation and machine learning, to elucidate charge-transport mechanisms and optimize defect chemistry.
4. Standardization and benchmarking — Formulation of uniform testing methodologies and reporting norms to guarantee reproducibility,

comparability, and industrial dependability of graphene-based devices.

5. Circular economy and life-cycle approaches — Integration of recycling strategies, green solvents, and low-carbon manufacturing to align graphene science with sustainability objectives.

Ultimately, the trajectory toward next-generation energy conservation systems will hinge on bridging the chasm between fundamental material science and industrial engineering. The convergence of nanomaterial creation, process scalability, and ecological accountability will determine whether graphene realizes its long-awaited function as a transformative facilitator of high-performance, lasting, and sustainable electrochemical energy storage methods [16], [19], [50]. Future research should prioritize multiscale modeling linking particle-level diffusion to electrode-level transport limitations. Standardization of gravimetric, areal, and volumetric metrics is required for realistic benchmarking. Integration of operando spectroscopy with impedance modeling will enable correlation between defect chemistry and kinetic parameters (D, Rct, b-value). Machine-learning-assisted materials design may accelerate optimization of graphene defect density and hybrid architectures.

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