



A Translational Roadmap of Emerging Research Fronts and Commercialization Opportunities in Graphene Sandwich Research Through Keyword Analysis

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Abstract-

Graphene sandwich structures have emerged as a versatile platform for advanced electrochemical, electronic and sensing devices owing to their tuneable interfacial physics and multilayer architectural synergy. Data for the analysis has been retrieved from the Web of Science core collection database, covering the period from 2004 to 2025, resulting in 949 documents. In this study a comprehensive keyword-based bibliometric analysis of graphene sandwich structures has been undertaken. Three complementary keyword analysis methods viz. keyword co-occurrence analysis, thematic mapping and factorial analysis have been used to uncover the intellectual structure and emerging trends of graphene sandwich structures. The co-occurrence network reveals dominant research clusters on mechanical reinforcement, energy storage, sensing, and multifunctional composites. Thematic map analysis provides deeper insight into the maturity and relevance of research themes by classifying them into motor, basic, niche, and emerging/declining themes. Factorial analysis further elucidates the conceptual relationships between keywords, enabling the classification of research directions into distinct knowledge domains. Vosviewer software is employed to generate the visualization maps and Biblioshiny was employed to quantify the structural prominence, bridging capacity and strategic influence of core keywords within the knowledge network analysis of the data through the network centrality indicators like betweenness, closeness and PageRank centralities. A key contribution of this work lies in systematically mapping these keyword clusters to their corresponding application potentials, followed by linking these applications to real-world products. This integrated framework provides valuable insights into the translational trajectory of graphene sandwich structures from fundamental research to industrial implementation, offering guidance for future research and innovation strategies.

Keywords: Graphene sandwich, keyword co-occurrence analysis, thematic map, factorial analysis, Vosviewer, Bibliometrix R package.

I. Introduction

Since the discovery of graphene in 2004, graphene and its 2D derivatives transformed materials science owing to their exceptional electrical conductivity, mechanical strength, and chemical stability. However, graphene exhibits a strong tendency toward restacking and agglomeration [1] which reduces ion-accessible surface area and limits out-of-plane charge transport in practical devices. Sandwich architectures have emerged as an effective structural strategy to overcome these intrinsic limitations by preserving accessible interfaces while improving charge and mass transport pathways.

The vertical integration of distinct 2D materials into graphene-based sandwich and heterostructures [2] enables properties beyond those of individual components. These architectures exploit van der Waals interactions [3] to tailor interfacial coupling, charge transport, and surface chemistry, thereby unlocking applications in electrochemical energy storage and conversion, including supercapacitors [4–6], rechargeable batteries [7], hydrogen evolution reaction (HER) systems [8,9], free-standing paper-like materials [10,11], catalysis [12] and nanoelectromechanical devices [13]. In electrocatalysis, graphene/TMDC sandwich heterostructures, incorporating MoS₂, have demonstrated enhanced HER performance [14] by combining graphene's high electrical conductivity with catalytically active edge sites of layered semiconductors. Three-dimensional (3D) graphene architectures incorporating carbon nanotubes (CNTs) suppress restacking, increase interlayer spacing, and create continuous electron transport pathways, improving electrochemical performance in supercapacitors and batteries. Graphene-based sandwich composites such as graphene/polyaniline/graphene papers combine electrical double-layer capacitance with pseudocapacitive behaviour of conducting polymers, resulting in devices with high energy and power densities in supercapacitor applications. Sandwich-structured graphene/metal-oxide composites further enhance lithium-ion [15–17] and sodium-ion [18], storage by accommodating volume changes and stabilizing active materials. Together, these advances illustrate how structural engineering at the nanoscale directly translates into improved device-level performance. Computational [16] and experimental studies further suggest that such architectures can accommodate guest species efficiently, supporting their use in advanced battery systems. Advanced fabrication strategies, including liquid-liquid self-assembly at oil/water interfaces [19] and at the interface between two immiscible electrolyte solutions (ITIES) [20] have enabled the production of transferable graphene-based films with tuneable electrochemical properties. Although ordered assembly of graphene/TMDC composites at ITIES remains limited, existing demonstrations of metal-nanoparticle-decorated graphene sandwiches [21] highlight their potential for enhancing interfacial charge transfer and capacitance.

The rapid expansion of graphene sandwich research is closely aligned with accelerating industrial demands in next-generation electronics, energy storage [22] and flexible device technologies [3]. The global push toward ultra-low-power electronics, neuromorphic architectures and quantum information technologies has intensified interest in graphene-based van der Waals heterostructures for memory and high-mobility transistors [23]. Simultaneously, the growth of electric vehicles and renewable energy integration requires high-energy-density, fast-charging, and durable storage systems, where graphene sandwich architectures [24] enhance quantum capacitance, charge-transfer kinetics, and structural robustness. Wearable electronics [25], flexible displays and Internet-of-Things (IoT) [26] technologies further demand lightweight and mechanically resilient materials-attributes inherently suited to graphene-based sandwich composites. These converging technological pressures are driving a transition from fundamental materials exploration toward application-oriented innovation.

Despite these extensive advancements, the field of graphene sandwich structures has become increasingly diverse and fragmented across material combinations, synthesis strategies, and device platforms. While numerous experimental and theoretical studies report performance improvements, a unified framework that quantitatively captures the intellectual structure, thematic evolution, and translational shift from fundamental heterostructure engineering to market-driven device innovation remains absent. The rapid proliferation of keywords related to interfacial engineering, multifunctional composites and device integration further complicates the ability to identify dominant research trajectories and emerging application priorities through conventional narrative reviews alone. Consequently, a systematic scientometric investigation is essential to map the conceptual architecture, application domains, and industry-oriented progression of graphene sandwich research.

The present work fills this gap through a comprehensive keyword-based analysis of the literature on graphene sandwich structures. This bibliometric study offers a quantitative and holistic perspective on how graphene sandwich structures have derived the technological advances various domains of technological interests. The outcomes of this analysis are expected to shape and support the strategic development of graphene-based sandwich structure research. The rationales of this study are to

1. Study the temporal progression of scholarly publications related to graphene sandwich structures.

2. Delineate the dominant research themes and their structural interrelationships through author keyword co-occurrence networks and advanced cluster analysis techniques.
3. Utilize thematic map analysis to systematically assess the centrality, density, maturity, and developmental trajectory of research themes across different evolutionary stages.
4. Elucidate the underlying intellectual architecture and latent conceptual structures of the field using factorial analysis.
5. Examine the temporal dynamics of high-frequency keywords to capture evolving research trajectories, emerging phenomena and application-driven thematic shifts.
6. Identify the most influential and recurrent keywords in graphene sandwich structures research, map their corresponding application domains and further investigate commercially mature application areas, associated products and leading industrial stakeholders driving technological translation.

II. Methodology

The Web of Science (WoS) database represents a comprehensive, globally recognized repository, which is widely acknowledged for its reliability and coverage. The data from WoS can be exported in several formats which is compatible with the bibliometric analysis software. Bibliometric data for the present study were retrieved from the WoS core collection covering the period from January 2004 to March 2025. Publications written in English were included. All relevant metadata fields including titles and keywords were extracted and utilized for bibliometric analysis. The search query was framed using the Boolean operators in the title field of the WoS data collection. The following query in the 'title field' of WoS core collection resulted 949 documents.

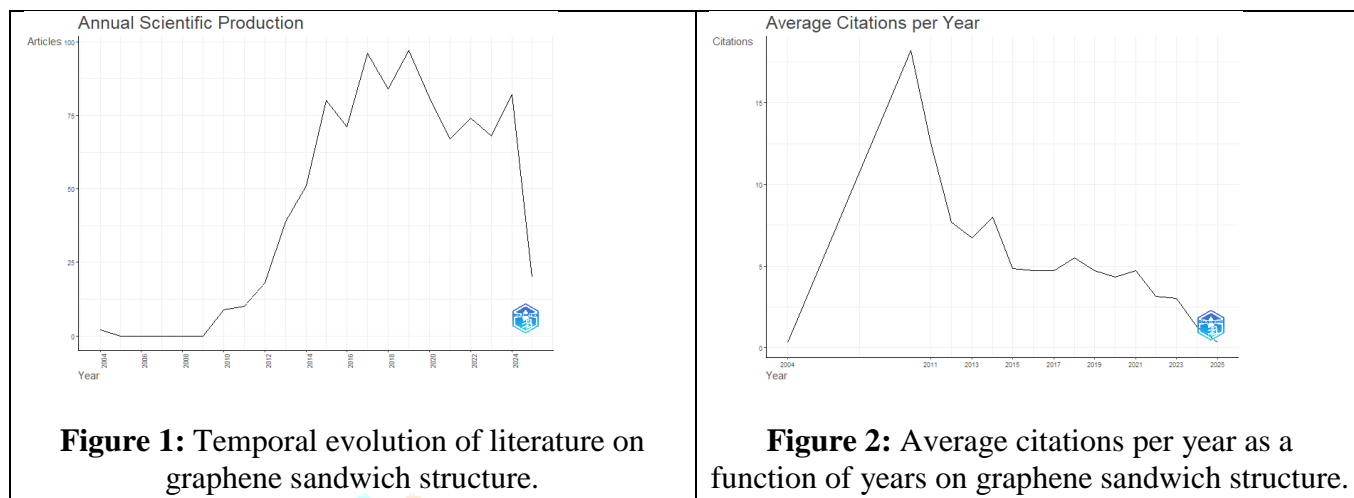
TI:(Graphene) OR (Graphene Oxide) OR (Graphite)) AND (Graphene Sandwich))

The metadata report obtained through biblioshiny is shown in Table 1 with 2072 keywords on the graphene sandwich structures.

Timespan	2004:2025
Sources	310
Documents	949
Annual Growth Rate %	11.59
Document Average Age	7.4
Average citations per doc	45.57
References	32206
Keywords Plus (ID)	2125
Author's Keywords (DE)	2072
Authors	3963
Authors of single-authored docs	21

III. Results and Discussion

The publication trend for graphene sandwich structures is illustrated in figure 1. The graph shows a significant peak in 2019, with a maximum of 97 papers published, followed by 96 and 84 papers in 2017 and 2018, respectively. The mean total citations per year were highest in 2010. After 2010, a continuous



decline in the mean total citations per year is observed as shown in figure 2.

Present metadata finds a total of 2072 author keywords. The search result for the analysis was narrowed down by filtering the co-occurrences of keywords as 3. Total 3 clusters were formed containing 171 keywords as shown in figure 3. First cluster contains 70 keywords. Keywords present in the first cluster can be divided into sub-clusters according to their relevance. Cluster's keyword analysis represents a strongly application-driven research theme focused on sandwich-structured and hybrid graphene-based nanomaterials for electrochemical energy devices, multifunctional nanodevices, electrocatalysis, clean energy, high-performance biosensing and diagnostics systems. The keywords reveal intensive research on 3D graphene, graphene nanosheets, reduced graphene oxide, carbon nanotubes, porous carbon, boron nitride, and hybrid composites, combined through layer-by-layer assembly, chemical vapor deposition, hydrothermal synthesis and sandwich-like or sandwich-type architectures.

a. Keyword Co-occurrence Analysis

The frequent occurrence of electrochemistry, electrochemical performance, electrocatalysis, oxygen reduction reaction (ORR), fuel cells, photocatalysis, plasmonics, and electromagnetic interference indicates a strong emphasis on electrochemical and catalytic functionality. At the same time, biosensor, electrochemical sensor, electrochemical immunosensor, aptamer, sensitivity, signal amplification, electrochemiluminescence and hydrogen peroxide point to advanced bioanalytical and diagnostic applications. Energy-storage relevance is evident from supercapacitor, asymmetric supercapacitor, lithium-ion batteries, sodium-ion batteries, anode, sandwich-type electrode and synergistic effect, while the inclusion of gold nanoparticles, silver nanoparticles, silver nanowires, MnO_2 , Co_3O_4 , TiO_2 , MoS_2 , metal-organic frameworks (e.g., MIL-101), polyaniline, polydopamine and chitosan highlights multifunctional hybridization strategies. Overall, this cluster reflects a mature research theme where sandwich-structured graphene hybrids are engineered to simultaneously enhance charge transport, catalytic activity, and sensing capability for energy, environmental and biomedical applications.

Enhanced Sensors			
Hybrid Nanocomposites & Structural Design	sandwich-like structure, sandwich-structured, sandwich-type electrode, layer-by-layer assembly, hybrid, synergistic effect	Multifunctional electrodes with enhanced stability and conductivity. Integrated sensing–energy platforms	Pan et. al. [22]
Characterization & Performance Evaluation	transmission electron microscopy, electrochemical performance, mechanical properties	Structure–property correlation and device optimization	Sagar et. al. [4]

Cluster 2 contains 56 keywords and represents a well-defined research theme focused on the nonlinear mechanical and Multiphysics analysis of graphene-reinforced sandwich and functionally graded composite structures with clear application relevance. The keywords indicate intensive studies on bending, nonlinear bending, buckling, buckling analysis, dynamic instability, free vibration, nonlinear vibration, nonlinear dynamic response, temperature-dependent vibration, strain and wave propagation in sandwich plates, sandwich beams, lattice sandwich plates, sandwich cylindrical shells, honeycomb cores, and foam-core structures, which are widely used in aerospace, automotive, marine and lightweight civil engineering applications. Aerospace and automotive lightweight structures, where resistance to buckling and vibration is critical under thermal and dynamic loading. They are also relevant to marine structures, high-speed rail components, and precision mechanical systems, where dynamic stability and wave propagation control directly affect safety, fatigue life and noise mitigation.

Table 3: Cluster 2 (Green): Lightweight structural and smart multifunctional systems for Electromagnetic and energy-storage technologies

Cluster	Keywords	Mapped Applications	References
Structural Mechanics & Stability	bending, nonlinear bending, buckling analysis, dynamic instability, free vibration, nonlinear vibration, nonlinear dynamic response, temperature-dependent vibration, strain, wave propagation	Aerospace and automotive lightweight structures, marine structures, high-speed rail components, and precision mechanical systems.	Palomba et. al. [36], Ma and Elkin [37]
Sandwich, Lattice, and Cellular Structures	sandwich plate, sandwich beam(s), lattice sandwich plate, sandwich cylindrical shell, sandwich structures, honeycomb core, foam core	Aircraft panels, satellite and launch vehicle components, ship hulls, wind turbine blades, and impact-resistant civil infrastructure	Kamble et. al. [38], D. Wannaronga and T. Singhanart [39]
Graphene-Based Reinforcement & Nanocomposites	graphene nanoplatelet(s), GPLs, graphene platelets, graphene platelet-reinforced composites, graphene origami, nanocomposites, polymer-matrix composites	Aerospace, automotive, flexible electronics packaging, and protective coatings, deployable and morphing structures.	Ezzati et. al. [40]

Functionally Graded and Porous Materials	functionally graded materials, porosity, porous materials, porous structures, mesoporous carbon, foam core	Thermal barrier structures, lightweight load-bearing panels, acoustic insulation systems, and biomedical-inspired porous scaffolds.	Kiarasi et. al. [41]
Advanced Modeling and Theoretical Methods	analytical solution, iso-geometric analysis, differential quadrature method, nonlocal strain gradient theory	Design optimization, predictive modeling, and digital prototyping	Mohammadimehr et. al. [42]
Smart Functional Effects, Electromagnetic and Energy-Related Applications	electrical properties, piezoelectric, magnetic field, temperature-dependent behavior, ZnO, microwave absorption, mesoporous carbon, n-doped, lithium-sulfur battery, shuttle effect	Smart structures, sensors, actuators, vibration control systems, and structural health monitoring, robotics, and microelectromechanical systems (MEMS), radar and microwave absorbers	Ntayeesh et. al. [43], Hussain et. al. [44]

Keywords sandwich plate, sandwich beam(s), lattice sandwich plate, sandwich cylindrical shell, sandwich structures, honeycomb core, foam core highlight applications in aircraft panels, satellite and launch vehicle components, ship hulls, wind turbine blades, and impact-resistant civil infrastructure, where high stiffness-to-weight ratios and energy absorption are essential. Honeycomb- and foam-core sandwich designs are particularly important for crashworthiness and vibration damping.

The use of graphene nanoplatelets (GPLs), graphene platelets, graphene platelet-reinforced polymer-matrix nanocomposites, and graphene origami points to efforts aimed at enhancing structural efficiency, vibration suppression, and stability performance. Methodological emphasis on analytical solutions and iso-geometric analysis. These keywords are associated with next-generation structural nanocomposites for aerospace, automotive, flexible electronics packaging, and protective coatings, where graphene reinforcement enhances mechanical strength, electrical conductivity, and multifunctionality. Graphene origami concepts further indicate applications in deployable and morphing structures. Keywords like functionally graded materials, porosity, porous materials, porous structures, mesoporous carbon, foam core points the usage in thermal barrier structures, lightweight load-bearing panels, acoustic insulation systems, and biomedical-inspired porous scaffolds, where gradual property variation and controlled porosity enable optimization of thermal resistance, vibration damping, and weight reduction.

Keywords present in this sub-cluster are analytical solution, iso-geometric analysis, differential quadrature method, nonlocal strain gradient theory etc. Although the keywords are methodological, this subgroup underpins design optimization, predictive modeling, and digital prototyping of nanoscale and microscale structures used in high-performance engineering systems, reducing experimental cost and accelerating industrial adoption of graphene-based sandwich composites.

Furthermore, the presence of electrical properties, piezoelectric effects, magnetic fields, microwave absorption, porosity, ZnO, mesoporous carbon, and lithium-sulphur battery-related materials reveal applications extending beyond structural mechanics to smart structures, sensors and actuators, electromagnetic interference (EMI) shielding, microwave absorbers and multifunctional energy-related components. Overall, this cluster reflects a mature, application-oriented research theme integrating lightweight structural design, smart multifunctional systems, and advanced graphene-based sandwich composites.

Collectively, these keyword subgroups reveal that Cluster 2 bridges lightweight structural engineering, smart multifunctional systems, electromagnetic applications, and energy-storage technologies, positioning graphene-reinforced sandwich composites as versatile platforms for advanced aerospace, automotive, defense, electronics and energy applications.

Third cluster Cluster 3 has 44 keywords and represents a multidisciplinary research theme centered on graphene-based and two-dimensional (2D) material nanostructures for electrochemical energy storage, sensing and catalytic applications. The keyword set shows a strong convergence of 2D materials, graphene, graphene oxide (GO), reduced graphene oxide (rGO), graphene quantum dots, carbon nanotubes, heterostructures, nanocomposites and sandwich architectures, indicating intensive efforts toward designing hierarchical and self-assembled nanostructures with tailored electrical and electrochemical functionality. Keywords like chemical synthesis, hydrothermal method, electrodeposition, laser-induced graphene, self-assembly, sandwich structure and sandwich architecture point towards the electrode fabrication, hierarchical architectures for high surface area energy devices.

Keywords such as energy storage, lithium-ion batteries, supercapacitors, anode materials, proton exchange membranes, hydrogen evolution reaction and hydrogen storage clearly point to electrochemical energy conversion and storage applications. The frequent appearance of electrochemical properties, electrochemical measurements, electrodes, conductivity, doping and electrodeposition highlights the dominant focus on charge transport and interfacial electrochemistry. While density functional theory and molecular dynamics reflect complementary theoretical and atomistic modeling to understand structure–property relationships.

Hydrogen evolution reaction, hydrogen storage, LDH, nanoparticles and nanostructures points the applications in hydrogen storage materials for clean energy technologies. Presence of keywords nanocomposite, composites, polypyrrole, proton exchange membrane, periodic mesoporous silica encompasses functional composite Materials leading to fuel cells, conductive and multifunctional composite electrodes.

Photodetector, surface plasmon resonance, surface-enhanced Raman spectroscopy, Raman spectroscopy, and laser-induced graphene indicate applications in optoelectronic devices and chemical/biological sensing. Overall, this cluster captures a mature and application-driven research direction focused on functional graphene-based nanomaterials enabling next-generation energy devices, catalysts and sensors.

Table 4: Cluster 3: Blue, Graphene based nanostructures for sustainable energy systems, advanced sensors, and flexible electronic devices

Cluster	Keywords	Mapped Applications	
Graphene & 2D Materials	2D materials, graphene, graphene oxide, rGO, graphene quantum dot, carbon nanotubes, heterostructure, two-dimensional materials	Electrodes for lithium-ion batteries and supercapacitors, Flexible and wearable energy devices, High-sensitivity chemical and biosensors	Nian et. al. [45]
Fabrication & Synthesis Routes	chemical synthesis, hydrothermal method, electrodeposition, laser-induced graphene, self-assembly, sandwich structure, sandwich architecture	Scalable electrode fabrication, hierarchical architectures for high surface area energy devices	Song et. al. [46]
Electrochemical Energy Storage & Conversion	energy storage, lithium-ion batteries, supercapacitors, anode material, electrode, electrochemical properties, electrochemical measurement, conductivity, doping.	Rechargeable batteries (LIBs), High-power supercapacitors, Electrochemical capacitive storage systems	Tang et. al. [47]

Modeling & Characterization Techniques	density functional theory, molecular dynamics, vibration analysis	Predictive modeling of electrochemical performance, Design optimization of 2D material-based devices	Chen et. al. [48]
Hydrogen and Catalytic Applications	hydrogen evolution reaction, hydrogen storage, LDH, nanoparticles, nanostructures	Electrocatalysts for water splitting, Hydrogen storage materials for clean energy technologies	Dutta et. al. [9], Yang et. al. [8]
Polymer- and Composite-Based Functional Materials	nanocomposite, composites, polypyrrole, proton exchange membrane, periodic mesoporous silica	Fuel cells and PEM technologies, Conductive and multifunctional composite electrodes	Wang et. al. [49]
Sensing & Optoelectronic Applications	photodetector, surface plasmon resonance, surface-enhanced Raman spectroscopy, Raman spectroscopy, adsorption	Gas and chemical sensors, Biosensing and environmental monitoring, Photodetectors and plasmonic devices	Liang et. al. [50]. Li et. al. [51]

b. Temporal Evolution of Research Themes

The trend-topic analysis reveals a clear temporal progression in graphene-based research, marked by a shift from foundational material studies to structurally complex and multifunctional applications as depicted in figure 4. In the early phase (2012–2014), research activity is dominated by general material-centric terms such as nanostructures, hybrid, lithium-ion batteries, and energy storage, indicating an initial focus on exploring graphene as an emerging functional material for energy storage and nanotechnology applications. During the intermediate phase (2015–2018), the thematic emphasis shifts toward compositional tuning and hybridization, as reflected by the increasing prominence of reduced graphene oxide, graphene oxide, nanocomposites, and carbon-based composites. Keywords like supercapacitors and lithium ion batteries signify the consolidation of graphene into engineered material systems, with growing attention to electrochemical performance and scalable fabrication routes. In the recent phase (2019–2021), structurally explicit keywords such as sandwich structure, sandwich-like structure, layer-by-layer assembly, sandwich-type electrode, graphene platelets, self-assembly and mos2 are highlighting a transition toward architectural design strategies aimed at enhancing synergistic effects, mechanical stability, and multifunctionality. Concurrently, application-oriented terms related to anode materials, lithium–sulphur batteries, and energy storage devices indicate increasing maturity at the device level. The latest phase (2022–2024) is characterized by the rise of advanced functional and physics-driven themes, including graphene nanoplatelets, free vibration, buckling, piezoelectric, electromagnetic interference shielding, and graphene origami. These topics reflect the extension of graphene sandwich and heterostructure concepts beyond electrochemical systems into structural mechanics, smart materials, and multifunctional engineering applications.

Overall, the temporal map illustrates a coherent evolution from material discovery, through hybrid and sandwich-structured design, to high-level functional integration, underscoring the increasing sophistication and application readiness of graphene-based research. This progression highlights the central role of architectural engineering in translating graphene's intrinsic properties into advanced technological systems.

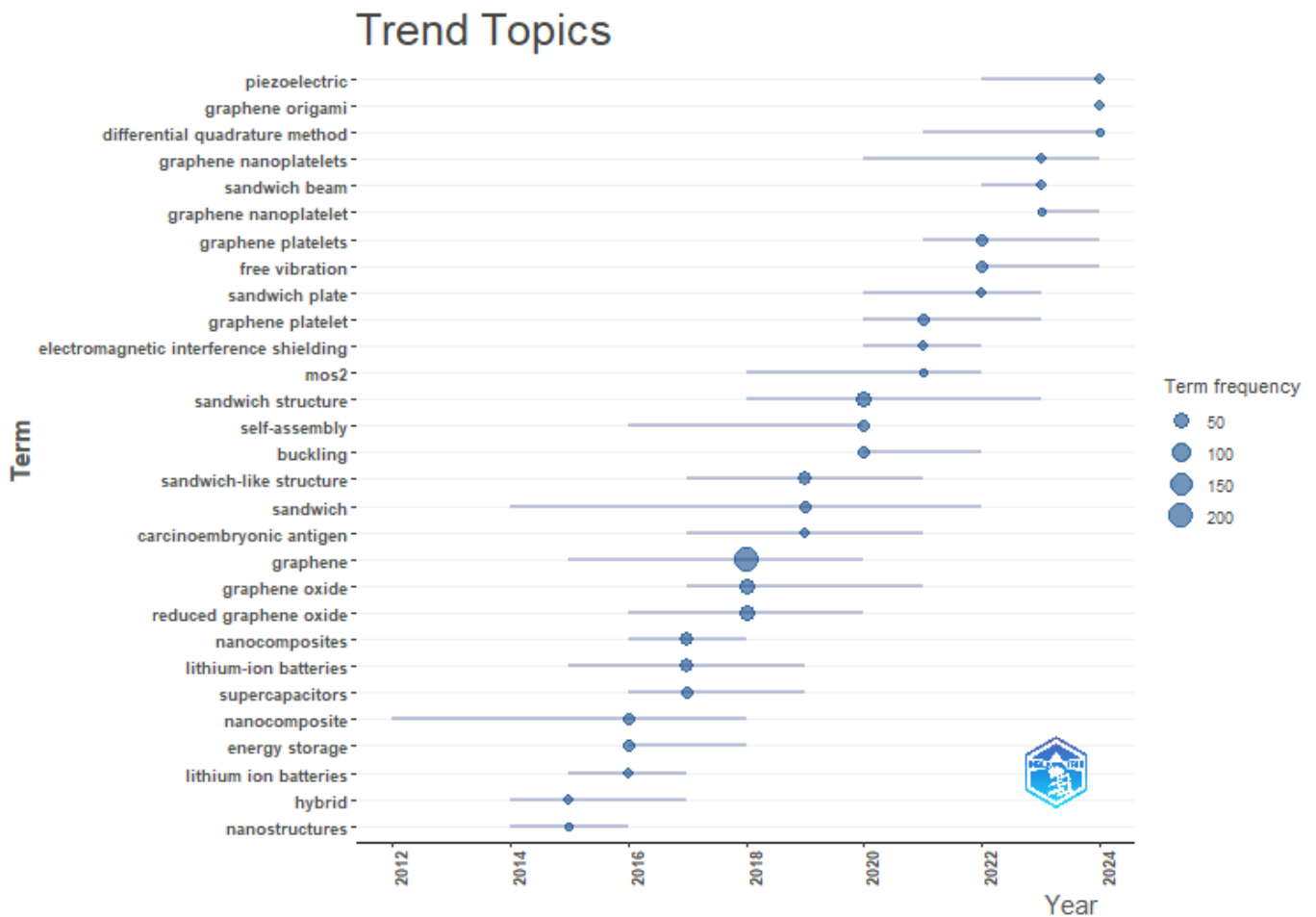


Figure 4: Temporal evolution of keywords in graphene sandwich structures obtained through Biblioshiny.

c. Thematic map Analysis

Thematic map [52] has four different quadrants as shown in figure 5. The themes in the motor quadrant have high centrality and high density. These are dominant, well-developed and field-driving themes. This quadrant is characterized by keywords such as graphene platelets, free vibration, and gold nanoparticles. These themes exhibit strong internal cohesion and high relevance to the overall research field, indicating mature and actively driving research directions. The presence of graphene platelets reflects advanced structural and mechanical exploitation of graphene, while free vibration signifies the integration of graphene-based materials into structural dynamics and mechanical performance studies. The inclusion of gold nanoparticles highlights hybrid material systems where graphene interacts synergistically with plasmonic or metallic components, underscoring multifunctional and performance-oriented applications.

Statistical parameters related to various clusters present in the motor theme cluster are given in Table 5. Betweenness, closeness, and PageRank centralities [53] are fundamental measures in network-based statistical analysis in bibliometric studies. Betweenness centrality identifies nodes that act as bridges and control information flow. Key words like graphene platelets, hydrogen peroxide, graphene nano-platelets and porous materials have the greatest betweenness centrality in their respective clusters, exhibiting their central importance in the network. The clusters in the table are presented in the hierarchical order of betweenness centralities. Closeness centrality reflects how efficiently a node can access others in the network and PageRank centrality evaluates the overall influence of a node based on the quality and quantity of its connections. Together, these metrics help reveal structural importance, knowledge diffusion patterns and influential entities within complex research networks.

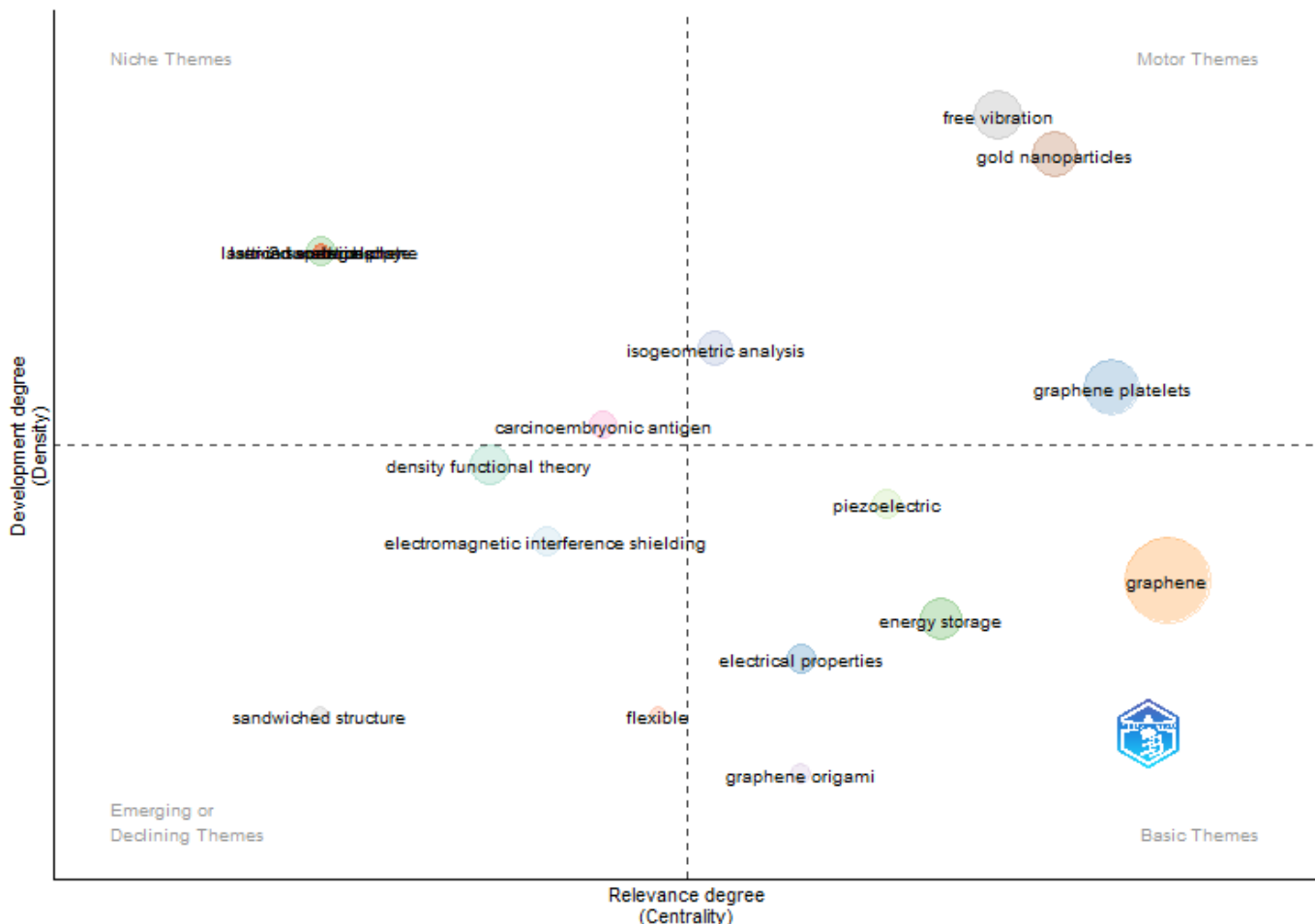


Figure 5: Thematic map of graphene sandwich structures encompassing author keywords.

Table 5: Motor theme quadrant

Graphene Platelets			
keywords	Betweenness centrality	Closeness centrality	Page Rank centrality
graphene platelets	983.8083498	0.001404494	0.011858344
graphene platelet	935.7614025	0.00132626	0.006024297
buckling	879.0886323	0.001488095	0.007732279
Gold Nano-particles			
hydrogen peroxide	546.5398144	0.001497006	0.00503838
electrochemical immunosensor	540.4243068	0.001550388	0.004385227
gold nanoparticles	282.0701556	0.001477105	0.006582512
Free Vibration			
graphene nanoplatelets	1323.40689	0.001451379	0.006675114
free vibration	884.42027	0.00124533	0.010639482
magnetic field	591.2856925	0.001283697	0.005415311
Iso-geometric analysis			
porous materials	591.6125397	0.001297017	0.004335179
isogeometric analysis	342.3054542	0.001308901	0.005007816
graphene platelets reinforcement	14.28368014	0.001003009	0.003180055

Basic themes quadrant is characterized by high centrality and low density. Themes in this quadrant are fundamental and transversal with broad relevance. The basic themes quadrant includes keywords such as graphene, energy storage, electrical properties, piezoelectric, and graphene origami. These topics are highly

central to the research field but exhibit relatively lower internal development, suggesting they function as foundational or enabling concepts. Graphene itself anchors the entire thematic structure, while energy storage and electrical properties represent broad application domains that connect multiple specialized research streams. Graphene origami indicates emerging structural design concepts that are gaining relevance but are still consolidating in terms of thematic maturity. The centrality evaluation of few basic theme clusters is shown in Table 6.

Table 6: Basic theme quadrant			
Graphene			
keywords	Betweenness centrality	Closeness centrality	Page Rank centrality
graphene	9339.176371	0.001923077	0.104809359
graphene oxide	4696.78765	0.001706485	0.022882732
Sandwich structure	3698.840944	0.001658375	0.027233556
Energy storage			
energy storage	295.1621271	0.001355014	0.007076055
composites	294.7023647	0.001574803	0.00543871
electrochemical properties	247.0240677	0.00136612	0.003766271
piezoelectric			
graphene nanoplatelets	467.0212697	0.001351351	0.005295341
Graphene origami			
graphene origami	136.1621139	0.001006036	0.002648345
electrical properties			
electrical properties	85.74726281	0.001287001	0.005880936

Themes specified by low centrality and high density are known as niche themes. These themes are internally cohesive, specialized but of marginal relevance. This quadrant contains tightly clustered yet peripheral topics such as laser-induced graphene and localized plasmonic structures, indicated by the small, dense cluster. These themes show strong internal development but limited connectivity to the broader field, suggesting specialized or technique-specific research. Such themes often represent high-precision fabrication or niche functional applications. These themes may be scientifically advanced but currently have restricted interdisciplinary influence.

Weakly developed and marginal themes are known as emerging or declining themes having low centrality and low density. Keywords including sandwich structure, flexible, graphene origami, density functional theory and electromagnetic interference shielding appear in this quadrant. Their low density and centrality indicate themes that are either at an early stage of development or losing prominence. In the context of graphene research, this positioning suggests that while sandwich structures and flexible architectures are conceptually promising, they are still undergoing consolidation or are transitioning toward other dominant thematic areas such as multifunctional energy and structural systems.

d. Co-word analysis

Keyword co-occurrence analysis, traditionally known as Co-word [54] of graphene sandwich structures is shown in figure 6. The colour-coded clustering reveals a graphene-centred thematic organization structured by co-occurrence relationships among keywords. The blue cluster (Cluster 1) is the largest and most centrally located. It represents the core research theme and encompasses foundational studies on graphene, reflecting its dominant role in defining the intellectual structure of the field. This cluster reveals keywords like graphene, nanocomposites, electrical conductivity, mechanical properties, thermal conductivity, hydrogen storage and density functional theory. These keywords can be mapped to applications of graphene sandwich in energy storage systems, thermal management materials, hydrogen storage media, and multifunctional engineering components. Cluster 2, the green cluster, closely connected to the core cluster, contains terms like lithium-ion batteries, supercapacitors, energy storage, MoS₂, nanostructures and electrochemical performance.

These keywords correspond to application-oriented research which leads to the device forming potential of graphene sandwich in devices like lithium-ion batteries, supercapacitors, hybrid energy storage systems, portable electronics and electric vehicles. In contrast, the red and orange clusters, which are more dispersed and positioned further from the centre, represent specialized and application-specific themes, including energy storage, sensing, and hybrid or composite architectures, where graphene is combined with complementary materials to achieve enhanced performance. Smaller peripheral clusters indicate emerging or niche research directions with weaker connectivity to the core theme. Overall, the clusters highlight a thematic structure, with fundamental graphene research forming the central knowledge base and progressively diversifying into applied and technologically oriented domains. Table 7 represents the centrality details of first few members of the dominant clusters in the hierarchy of betweenness centrality.

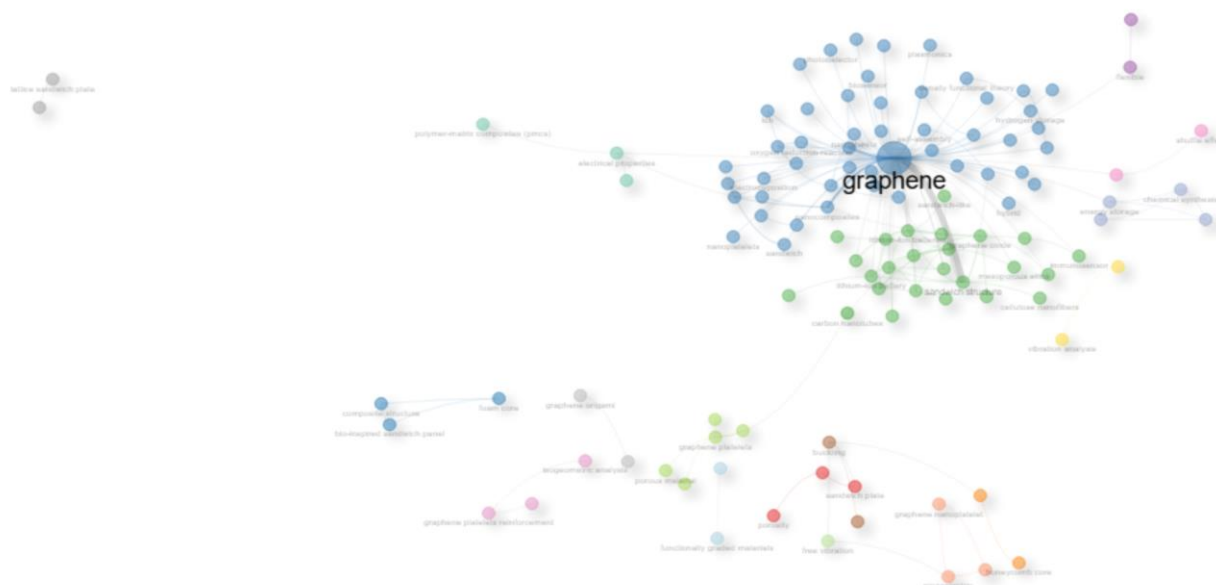


Figure 6: Co-word analysis visualization map.

Table 7: Centrality Details of First Few Keywords

Node	Cluster	Betweenness	Closeness	PageRank
graphene	1	3547.724428	0.007874016	0.19719388
nanocomposites	1	112.0950728	0.004878049	0.016827505
supercapacitor	1	91.48333333	0.004830918	0.021289097
reduced graphene oxide	2	506.9343911	0.004149378	0.019911184
sandwich structure	2	423.2144576	0.005291005	0.032668819
graphene oxide	2	92.5577219	0.003968254	0.013350373

e. Factorial Map Analysis

The factorial map [55] of the graphene sandwich structure is shown in figure 7. The left region of the map is dominated by keywords such as porous carbon, composite, supercapacitor, oxygen reduction reaction, and polymer, indicating foundational research focused on carbon-based materials, charge storage mechanisms and electrochemical functionality. Moving toward the central region, keywords including sandwich structure, sandwich-type electrode, hybrid, reduced graphene oxide, graphene nanosheets, and metal–organic frameworks emerge, reflecting a shift toward hybrid material design and sandwich-structured graphene architectures aimed at synergistically enhancing conductivity and stability. The rightmost region features structurally and mechanically oriented terms such as graphene platelets, carbon

nanotubes, buckling, vibration, and sandwich plate, highlighting the extension of graphene sandwich concepts into structural mechanics and multifunctional load-bearing systems. Overall, the movement along x-axis reveals the transitions from basic electrode materials and electrochemical concepts toward advanced structural architectures. Movement along y-axis the thematic progression reflects increasing functional sophistication and performance optimization. The lower portion emphasizes material composition and synthesis-related terms, including porous carbon, composite, and polymer, representing early-stage material development.

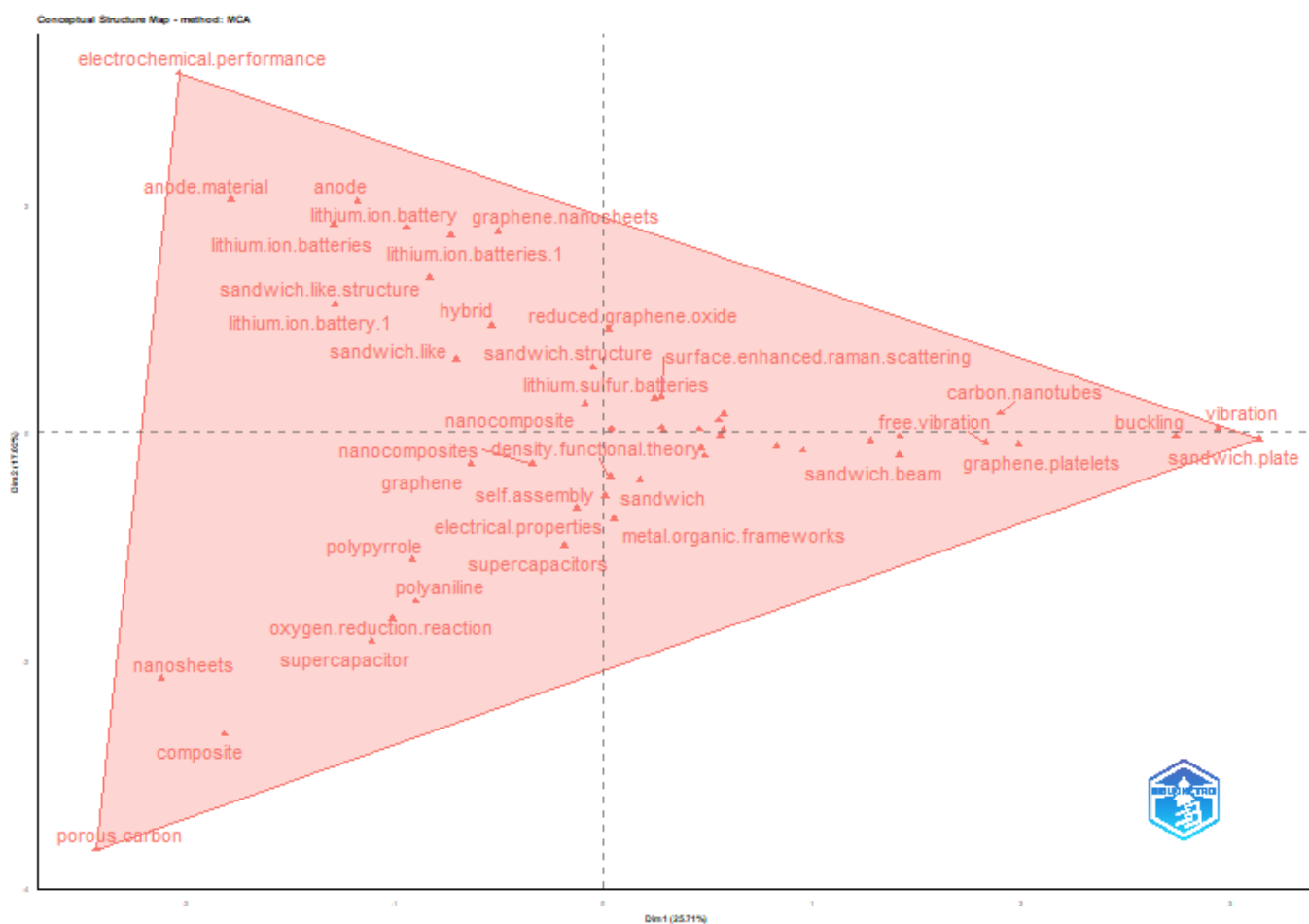


Figure 7: Factorial map of the graphene sandwich structure.

Ascending upward, keywords such as electrical properties, electrochemical performance, anode material, lithium-ion batteries, and lithium-sulphur batteries become prominent, indicating a focus on device-level performance and energy storage applications. At the top of the map, high-impact application-oriented terms such as anode, hybrid lithium-ion battery, graphene nanosheets and surface-enhanced Raman scattering, signify mature research themes centred on high-performance energy storage systems and advanced functional interfaces.

Overall, the factorial map reveals a coherent thematic trajectory in which graphene-based research evolves from fundamental carbon materials, through hybrid and sandwich-structured graphene architectures, toward multifunctional energy storage and structural applications, underscoring the central role of sandwich and hybrid graphene designs in bridging electrochemical performance and mechanical functionality.

f. Industrial Translation of Graphene Architectures and Heterostructures

Table 8 gives a connection between the extracted keywords from the metadata on graphene sandwich and realised commercial products through applications mapping of keywords.

Structure Type	Matched Keywords from clusters	Applications derived from Keywords	Products	Company Website link
Graphene Sandwich Structure	sandwich-type electrode, porous carbon, rGO, 3D graphene, electrochemical performance	Lithium-ion batteries, sodium-ion batteries, high-power supercapacitors	Graphene-based sandwich-type battery electrodes	Log9 Materials https://www.log9materials.com
Graphene Sandwich Structure	sandwich-like structure, hybrid, synergistic effect, electrode, conductivity	Enhanced conductivity and stability in lithium-ion battery electrodes	G+® graphene battery additives	Directa Plus S.p.A. https://www.directa-plus.com
Graphene Sandwich Structure	layer-by-layer assembly, sandwich-structured, hybrid nanocomposites	Multifunctional electrodes and membranes; integrated sensing–energy platforms	Graphene composite membranes / laminates	Directa Plus S.p.A. https://www.directa-plus.com
Graphene Heterostructure (2D–2D)	graphene, 2D materials, heterostructure, electrical properties	High-sensitivity electronic sensors for automotive and industrial systems	Graphene Hall-effect sensors	Paragraf Ltd. https://www.paragraf.com
Graphene Heterostructure (2D–2D)	graphene oxide, rGO, heterostructure, biosensor, electrochemical sensor	Chemical and biomedical biosensing platforms	Graphene molecular & biosensors	Paragraf Ltd. https://www.paragraf.com
Graphene Heterostructure (3D / hybrid)	graphene heterostructure, hybrid, synergistic effect, energy storage, electrode	High-energy-density lithium–sulfur batteries	3D Graphene™ Li–S battery electrodes	Lyten, Inc. https://lyten.com
Graphene Heterostructure (3D / hybrid)	graphene nanocomposites, hybridized systems, multifunctional structures	Lightweight structural components and multifunctional materials	3D Graphene™ reinforced composites	Lyten, Inc. https://lyten.co

The commercial landscape of graphene-based technologies reflects a sophisticated translation of theoretical architectures into functional industrial products.

In the domain of Graphene Sandwich Structures, the integration of sandwich-type electrodes and porous carbon has been successfully commercialized by Log9 Materials to optimize the electrochemical performance of lithium-ion and sodium-ion batteries, as well as high-power supercapacitors. Similarly, Directa Plus S.p.A. utilizes sandwich-like structures to leverage synergistic effects between graphene and active materials, resulting in G+® battery additives that enhance both conductivity and stability. Furthermore, the application of layer-by-layer assembly in sandwich-structured hybrid nanocomposites by Directa Plus has facilitated the development of multifunctional graphene membranes and laminates for integrated sensing–energy platforms.

The industrial adoption of graphene heterostructures is equally prominent. Paragraf Ltd. has utilized 2D-2D heterostructures to engineer high-sensitivity Hall-effect sensors for automotive and industrial systems. They have also used graphene heterostructures in graphene-based biosensors for chemical and biomedical sensing. In the field of 3D/hybrid heterostructures, Lyten, Inc. employs hybridized systems and synergistic effects to produce 3D Graphene™ lithium-sulphur (Li-S) battery electrodes designed for high-energy-density storage. Additionally, their use of 3D graphene nanocomposites has enabled the creation of multifunctional materials and lightweight structural components. These examples underscore the industrial viability of advanced graphene architectures in meeting the rigorous demands of modern energy and sensing applications.

IV Conclusions

Keyword co-occurrence analysis of first cluster serves as a motor theme, integrating sandwich-structured graphene hybrids, electrochemical energy devices, electrocatalysis, and biosensing technologies, with strong translational relevance to clean energy systems, biomedical diagnostics, and multifunctional nanodevices. Second cluster emphasise on lightweight structural engineering, smart multifunctional systems, electromagnetic applications, and energy-storage technologies, positioning graphene sandwich structures as versatile platforms for advanced aerospace, automotive, defence, electronics, and energy applications. Third cluster reflects a strongly application-oriented theme, linking graphene-based nanostructure designs for electrochemical energy storage and conversion, sensing devices, electrocatalyst, fuel cells and optoelectronic technologies. These mapped applications put graphene sandwich structures on a high pedestal for sustainable energy systems, advanced sensors, and flexible electronic devices.

The quadrant analysis of thematic map reveals a hierarchical and evolving research landscape, where foundational graphene concepts and energy-related applications occupy central positions, advanced mechanical and hybrid material systems act as motor themes, and specialized fabrication techniques remain niche. Importantly, several themes currently classified as emerging, such as sandwich structures and graphene origami, demonstrate strong potential to migrate toward motor or basic themes as their applications mature and integration increases.

The factorial map analysis disseminates an integrated research landscape in which graphene-based nanocomposites serve as a unifying platform, linking energy storage technologies with structural-dynamic applications, while simultaneously spanning from fundamental material design to advanced, high-performance engineered systems. In the factorial map, the thematic evolution progresses systematically from material fundamentals to structural complexity and performance-driven applications.

This keyword-based scientometric analysis demonstrates that graphene sandwich heterostructure research has transitioned from fundamental investigations of interlayer interactions to application-driven domains such as energy storage, flexible electronics, sensor technology and advanced device architectures. The prominence of themes related to interface engineering, van der Waals integration, and multifunctional composites reflects the increasing technological maturity of the field. By identifying emerging research clusters and thematic evolution, this study provides a structured perspective on current trends and future directions. These insights may support strategic research planning and accelerate the translation of graphene sandwich architectures into future electronic and energy systems.

The systematic mapping of metadata derived keywords to the commercial portfolios of companies demonstrates that graphene sandwich structures are not merely theoretical constructs but are foundational to the next generation of high-performance energy storage and multifunctional industrial products. Consequently, this keyword-driven analysis underscores the critical role these architectures play in bridging the gap between advanced materials research and the realization of commercially viable, high-sensitivity sensing and energy-dense battery technologies.

References

- [1] J. Li and M. Östling, *Crystals* **3**, 163 (2013).
- [2] C. Dean, A. F. Young, L. Wang, I. Meric, G.-H. Lee, K. Watanabe, T. Taniguchi, K. Shepard, P. Kim, and J. Hone, *Solid State Communications* **152**, 1275 (2012).
- [3] T. Georgiou, R. Jalil, B. D. Belle, L. Britnell, R. V. Gorbachev, S. V. Morozov, Y.-J. Kim, A. Gholinia, S. J. Haigh, O. Makarovskiy, L. Eaves, L. A. Ponomarenko, A. K. Geim, K. S. Novoselov, and A. Mishchenko, *Nature Nanotech* **8**, 100 (2013).
- [4] P. Sagar, I. R. Hamdani, T. Levato, V. Giannini, and G. Das, *Mater. Adv.* **7**, 83 (2026).
- [5] Q. Zhou, X. Chen, F. Su, X. Lyu, and M. Miao, *Ind. Eng. Chem. Res.* **59**, 5752 (2020).
- [6] S. Kumar, P. Bora, P. C. Bhomick, D. Rangappa, and D. Sinha, *Nano Research Energy* **4**, e9120148 (2025).
- [7] Y. Cao, X. Li, I. A. Aksay, J. Lemmon, Z. Nie, Z. Yang, and J. Liu, *Phys. Chem. Chem. Phys.* **13**, 7660 (2011).
- [8] L. Yang, X. Li, G. Zhang, P. Cui, X. Wang, X. Jiang, J. Zhao, Y. Luo, and J. Jiang, *Nat Commun* **8**, 16049 (2017).
- [9] T. Dutta, P. Chaturvedi, A. Thakur, and S. K. Mishra, *Energy Fuels* **39**, 8827 (2025).
- [10] D. A. Dikin, S. Stankovich, E. J. Zimney, R. D. Piner, G. H. B. Dommett, G. Evmenenko, S. T. Nguyen, and R. S. Ruoff, *Nature* **448**, 457 (2007).
- [11] S. Park, K.-S. Lee, G. Bozoklu, W. Cai, S. T. Nguyen, and R. S. Ruoff, *ACS Nano* **2**, 572 (2008).
- [12] Z.-S. Wu, W. Ren, L. Xu, F. Li, and H.-M. Cheng, *ACS Nano* **5**, 5463 (2011).
- [13] N. Kammoun, H. Jrad, S. Bouaziz, M. B. Amar, M. Soula, and M. Haddar, *J. Mech.* **35**, 65 (2019).
- [14] T. F. Jaramillo, K. P. Jørgensen, J. Bonde, J. H. Nielsen, S. Hørch, and I. Chorkendorff, *Science* **317**, 100 (2007).
- [15] W. Yue, S. Jiang, W. Huang, Z. Gao, J. Li, Y. Ren, X. Zhao, and X. Yang, *J. Mater. Chem. A* **1**, 6928 (2013).
- [16] E. Yoo, J. Kim, E. Hosono, H. Zhou, T. Kudo, and I. Honma, *Nano Lett.* **8**, 2277 (2008).
- [17] C. Tang, Q. Zhang, M. Zhao, J. Huang, X. Cheng, G. Tian, H. Peng, and F. Wei, *Advanced Materials* **26**, 6100 (2014).
- [18] J. Wang, J. Yang, W. Yin, and S. Hirano, *J. Mater. Chem. A* **5**, 20623 (2017).
- [19] S. Gan, L. Zhong, T. Wu, D. Han, J. Zhang, J. Ulstrup, Q. Chi, and L. Niu, *Advanced Materials* **24**, 3958 (2012).
- [20] Z. Samec, *Electrochimica Acta* **84**, 21 (2012).
- [21] P. S. Toth, M. Velický, Q. M. Ramasse, D. M. Kepaptsoglou, and R. A. W. Dryfe, *Adv Funct Materials* **25**, 2899 (2015).
- [22] S. Pan, J. Ren, X. Fang, and H. Peng, *Advanced Energy Materials* **6**, 1501867 (2016).
- [23] T. Kim, S. Fan, S. Lee, M.-K. Joo, and Y. H. Lee, *Sci Rep* **10**, 13101 (2020).
- [24] J. Zhu, D. Yang, Z. Yin, Q. Yan, and H. Zhang, *Small* **10**, 3480 (2014).
- [25] S. Dong, Q. Feng, and Y. Shi, *Sensors and Actuators A: Physical* **395**, 117022 (2025).
- [26] S. Ganguly and J. Sengupta, *Discover Nano* **19**, 110 (2024).
- [27] P. Simon and Y. Gogotsi, *Nature Mater* **7**, 845 (2008).
- [28] T. Kim, W. Song, D.-Y. Son, L. K. Ono, and Y. Qi, *J. Mater. Chem. A* **7**, 2942 (2019).
- [29] A. Manthiram, *ACS Cent. Sci.* **3**, 1063 (2017).
- [30] L. Dai, Y. Xue, L. Qu, H.-J. Choi, and J.-B. Baek, *Chem. Rev.* **115**, 4823 (2015).
- [31] J. Wang, W. Cui, Q. Liu, Z. Xing, A. M. Asiri, and X. Sun, *Advanced Materials* **28**, 215 (2016).
- [32] M. M. Sebastian, P. Velayudham, A. Schechter, and N. Kalarikkal, *Energy Fuels* **36**, 7782 (2022).
- [33] Y. Chen, N. Vicente, T. Pham, and A. Mulchandani, *Biosensors* **15**, 373 (2025).
- [34] W. Xu, L. Xie, J. Zhu, L. Tang, R. Singh, C. Wang, Y. Ma, H.-T. Chen, and Y. Ying, *Carbon* **141**, 247 (2019).
- [35] L. Wu, J. Guo, Q. Wang, S. Lu, X. Dai, Y. Xiang, and D. Fan, *Sensors and Actuators B: Chemical* **249**, 542 (2017).
- [36] G. Palomba, G. Epasto, and V. Crupi, *Mechanics of Advanced Materials and Structures* **29**, 4839 (2022).
- [37] W. Ma and R. Elkin, *Sandwich Structural Composites: Theory and Practice*, 1st ed. (CRC Press, Boca Raton, 2021).
- [38] Z. Kamble, *Polymer Composites* **45**, 16355 (2024).
- [39] D. Wannarong and T. Singhanart, *EJ* **26**, 27 (2022).

- [40] H. Ezzati, F. Ebrahimi, and E. Salari, *JCAMECH* **56**, (2025).
- [41] faraz kiarasi, masoud babaei, P. Sarvi, kamran asemei, mohammad hosseini, and M. Omidi Bidgoli, *J Appl. Comput. Appl. Mech.* **52**, (2021).
- [42] M. Mohammadimehr, M. Mehrabi, and F. S. Mousavinejad, *Journal of Vibration and Control* **27**, 1842 (2021).
- [43] T. J. Ntayeesh and M. Arefi, *Heliyon* **10**, e29436 (2024).
- [44] T. Hussain, T. Kaewmaraya, Z. Hu, and X. S. Zhao, *ACS Appl. Nano Mater.* **5**, 12637 (2022).
- [45] Q. Nian, L. Gao, Y. Hu, B. Deng, J. Tang, and G. J. Cheng, *ACS Appl. Mater. Interfaces* **9**, 44715 (2017).
- [46] G. Song, Q. Wang, L. Sun, S. Li, Y. Sun, Q. Fu, and C. Pan, *Materials & Design* **191**, 108629 (2020).
- [47] C. Tang, H.-F. Wang, J.-Q. Huang, W. Qian, F. Wei, S.-Z. Qiao, and Q. Zhang, *Electrochem. Energ. Rev.* **2**, 332 (2019).
- [48] Y. Chen, W.-T. Guo, Z.-S. Chen, S. Wang, and J.-M. Zhang, *J. Phys.: Condens. Matter* **34**, 125504 (2022).
- [49] M. Wang, X. Duan, Y. Xu, and X. Duan, *ACS Nano* **10**, 7231 (2016).
- [50] Z. Liang, M. Wang, X. Zhang, Z. Li, K. Du, J. Yang, S.-Y. Lei, G. Qiao, J. Z. Ou, and G. Liu, *ACS Nano* **18**, 3669 (2024).
- [51] X. Li, S. Lin, X. Lin, Z. Xu, P. Wang, S. Zhang, H. Zhong, W. Xu, Z. Wu, and W. Fang, *Opt. Express* **24**, 134 (2016).
- [52] Mario Angelelli, Enrico Ciavolino, Christian M. Ringle, Marko Sarstedt & Massimo Aria, *Quality & Quantity* **59**, 2753 (2025).
- [53] M. Newman, in *Networks*, 2nd ed. (Oxford University PressOxford, 2018), pp. 158–217.
- [54] QIN, HE, *LIBRARY TRENDS* **48**, 133 (1999).
- [55] Busrul Iman, Imam Yuadi et. al., *Sage Open* (n.d.).

