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Engineering integration of graphene aerogels in aerospace mechanics current state of research and future application

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Abstract

Graphene aerogel is an ultralight material with outstanding thermal, electrical, and mechanical properties, which positions it as a promising candidate for advanced aerospace engineering applications. Recent advances in additive manufacturing, including three-dimensional printing and bio-inspired fabrication strategies, have enabled the design of architected graphene aerogel structures that draw on hierarchical and cellular architectures found in natural systems. By translating biological structural principles into engineered materials, bio-inspired design allows precise control over porosity, load transfer, and functional grading, thereby enhancing strength-to-weight ratios, energy dissipation, and multifunctional integration, all of which are critical requirements for aerospace structures. This review examines the convergence of graphene aerogel research with these advanced fabrication approaches, highlighting their implications for structural efficiency, weight reduction, and the integration of sensing and electromagnetic interference (EMI) shielding functionalities. Despite persistent challenges related to mechanical fragility under extreme loading conditions, energy-intensive production routes, and scalability constraints, reported properties such as ultra-low densities as low as 3.13 mg/cm^3 and EMI shielding effectiveness of up to 87 dB at a thickness of 2.0 mm underscore the technological relevance of graphene aerogels. By synthesizing current literature and identifying key knowledge gaps, this work outlines critical research pathways grounded in bio-inspired design principles to advance the application of graphene aerogels in future aerospace structures.

Keywords Graphene aerogel, Additive manufacturing, Lightweight materials, Aerospace applications

1 Introduction

Composites represent high-tech materials applied in engineering, formed by the combination of two or more materials with distinct physical and chemical properties. These materials typically consist of a matrix or structural material and a reinforcement material that ensures the desired properties, generally related to strength, elasticity, and anisotropic characteristics. Among the composites that have gained prominence in industry, particularly in aviation, are polymers reinforced with fiberglass combined with graphene. The results of this interaction were presented in studies conducted by [1] where material damage was predicted by measuring the deviation of piezo resistance from the elastic response line using statistical analysis, suggesting potential applications for fiberglass composites coated with graphene oxide, a material with promising industrial applications [2].

Over the past five years, the use of graphene in polymer composition for manufacturing sports equipment, cars, and airplane wings and fuselages has been increasing, particularly in composites identified as carbon fiber-reinforced composites (CFRCs) [3, 4].As demonstrated by [5] in their study through Fig. 1, which presents the graphene cycle over the years with predictions for the future, in this context graphene emerges as a promising additive due to its aromatic chemical structure; its two-dimensional form, characterized by high proportionality that ensures flexibility and strength, whether as a surface coating for the fiber or as a connection between the material's different layers; and, finally, its ability to be produced on a large scale at room temperature without the need for metallic catalysts [6–8].

Although graphene-based technology has widespread applications ranging from the manufacturing of biomedical products, textiles, aerospace technologies, and printing technologies to the replacement of silicon in electrical systems, membranes, and energy storage devices, its relevance is primarily centered on spatial economy [9–14] demonstrated by in the Fig. 2 [15]. As a single material, graphene is a carbon allotrope arranged in a hexagonal lattice, with atoms bonded in an *Sp*2 configuration, and it can be layered with interplanar spacing to form graphite [16, 17].

Even though it has become a structural strategy for devices and equipment, traditional approaches such as surface coating, structural immersion, and 3D printing fail to

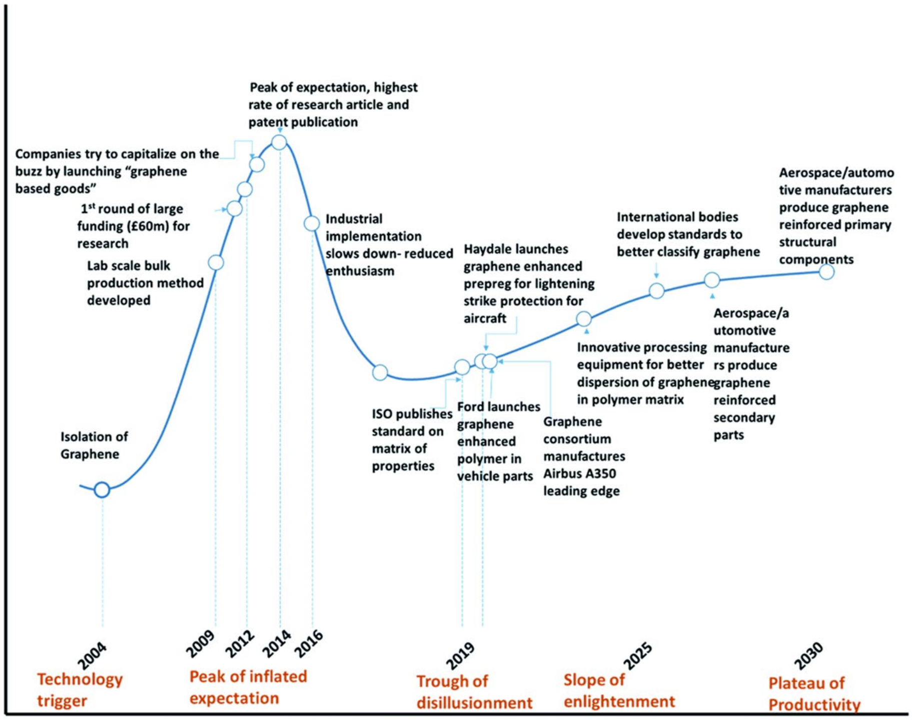


Fig. 1 The cycle of graphene along the years [5]

Fig. 2 Examples of how the material can be used in multiple fields [15]

adequately integrate the necessary combination for structuring and multifunctional performance [18]. Previous research discussed about the use of additive manufacturing and bioprinting in aviation [19].

- 3D and bioprinting technologies are used for producing complex, multifunctional materials [20–23].
- Bioprinting principles like spatial control, layer-by-layer precision, and multi-material integration are used for high-performance aerospace structures [24–26].
- Graphene-based materials, including aerogels, are suited due to their tunable morphology and compatibility with advanced deposition methods [27–29].
- Bioprinting-inspired approaches can integrate Graphene Aerogel into next-generation aerospace systems [30, 31].

Therefore, a better understanding of process-dependent structural stability requires knowledge of electrical conductivity as well as the multifunctional characteristics of mechanical, electrical, piezoresistive, and anisotropic Electronic performance, in the study provided by [32], Fig. 3 shows the graphical summary of the overall structures presented by the Graphene material in different arrangements. In aviation, this serves to develop an intelligent aircraft wing model with sensors capable of identifying freezing risks, providing high-temperature warnings, flame retardancy, pressure and vibration monitoring, as well as Electronic shielding and stealth capabilities [33].

The search for environmentally sustainable alternatives to conventional fossil fuel based systems positions electric aviation as a key frontier in aerospace innovation. Recent advances in instrumentation technology and quantum mechanics have highlighted the importance of nanomaterials, particularly carbon based nanostructured materials, metal oxides, and conductive polymers, in enhancing aircraft energy storage

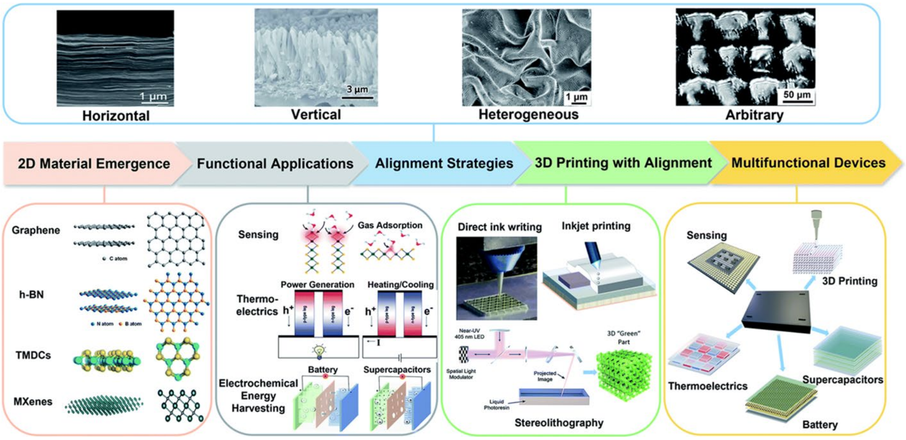


Fig. 3 Graphical summary of the material's internal structure, from 2D nanomaterial studies to functional applications, fabrication methods, and prospects for multifunctional devices [32]

and conversion systems [34, 35]. In addition to their role in batteries and electric propulsion systems, these materials are increasingly incorporated into aircraft components such as motors, pitot tubes, wings, fuselages, and windshields, where they can improve resistance to environmental exposure while contributing to drag reduction. Within this context, graphene aerogels have emerged as a promising class of materials due to their ultra-low density, high specific surface area, mechanical robustness, and electrical conductivity. These characteristics enable efficient charge transport and energy storage while maintaining structural integrity, making Graphene Aerogels suitable not only for discrete components but also for lightweight, multifunctional structural frameworks. Such capabilities suggest their potential to support integrated energy storage and load-bearing architectures in next-generation electric aircraft designs and aerospace models [36, 37].

Recognized as lightweight, high-performance materials, polymer composites with graphene-based carbon fiber coatings remain at the forefront among all composite materials, not only due to their strength-to-weight ratio compared to metallic components but also for their contribution to increased aircraft longevity and fuel efficiency [38, 39]. Ice formation on aircraft surfaces poses significant safety risks, and current detection systems often struggle to provide accurate real-time predictions, representing considerable challenges in general aviation transport [40, 41]. Today, the combination of conventional aircraft de-icing techniques has proven insufficient in ensuring safety and accident prevention. Experimental studies have shown that the incorporation of high-quality graphene into aircraft structures results in surfaces that exhibit higher contact angles, lower energy consumption, and greater heating efficiency compared to the use of traditional electrically heated materials for anti-icing applications [34, 42].

Another notable aspect in the use of innovative materials incorporated with graphene is observed in the construction of sensors that can be configured as conductors, semiconductors, or as sensitive markers that respond to corrosion factors. These sensors can be deposited on rigid and flexible sensor surfaces and interfaces, such as optical fibers and microelectrode structures, serving as corrosion monitoring tools [43]. Aligned to minimize the environmental issues caused by traditional aviation industries, which are particularly severe, a variety of advanced battery technologies and graphene-based nanomaterials show considerable potential. They reduce the time for part disposal due to battery thermal management and high power density, optimizing their recurrent use. However, the industry still faces deficiencies in the mass production process [44, 45].

Carbon materials have been used in the aerospace industry for a long period of time, and graphene composites are gaining prominence in the production of systems that include monitoring temperature transitions, thermal stability, chemical resistance, low physical deformation, longevity, among others [46–48], which was shown by [15] in his studies about the different properties presented by the materials tested in different temperatures (as shown in Fig. 4). However, conventional production methods for graphene composites remain costly, and despite enhancing the longevity of components for the industry, it is necessary to consider future disposal processes, as these materials do not decompose easily [49].

Thus, the main contributions of the present literature review can be described through the following points: (1) a general presentation of the most attractive properties of Graphene Aerogel and its respective manufacturing processes aimed at improving aircraft performance using this material; (2) identification of trends for the development of future works and products from an analytical perspective, focusing not only on the final result but also on the process to achieve it; (3) finally, a clear identification of how the use of Graphene Aerogel can significantly benefit aviation through the relationship between density and the relevance of the themes presented within the textual corpus.

This review primarily focuses on Graphene Aerogel as a core lightweight and multifunctional material platform for aerospace and aviation applications. In addition to pure graphene aerogels, graphene-aerogel-based hybrid systems are included when graphene aerogel constitutes the continuous structural or functional framework and governs key performance metrics such as mechanical stability, thermal insulation, or electromagnetic interference shielding. Aerogel systems that do not rely on graphene aerogel as the dominant phase are considered only for comparative and benchmarking purposes,

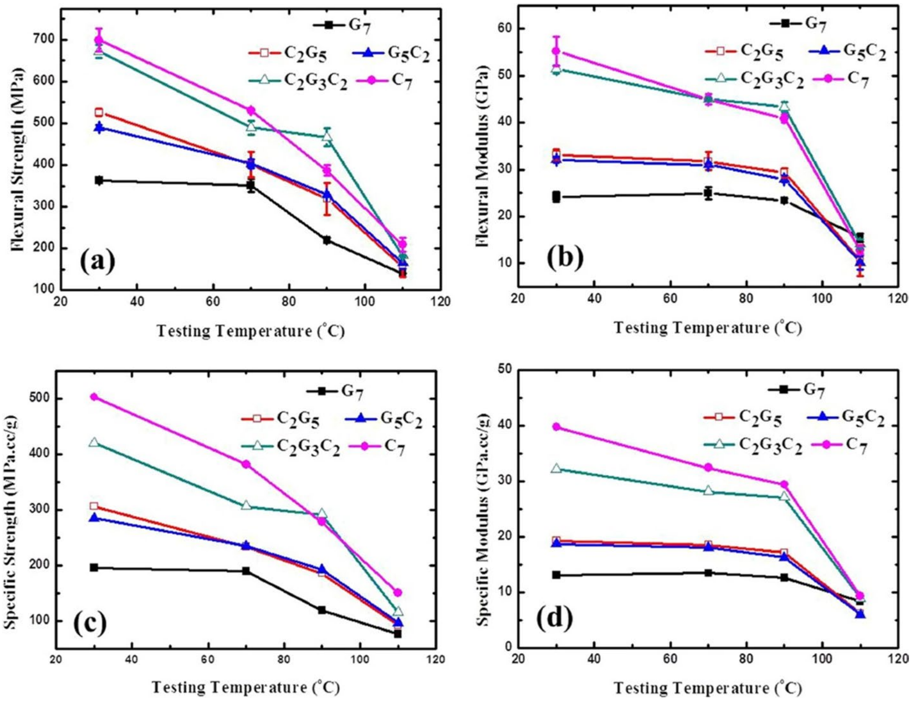


Fig. 4 Behavior of the graphene composites in different temperatures [15]

in order to contextualize performance trends, fabrication strategies, and application-driven design requirements relevant to graphene aerogel development in aerospace engineering.

2 Materials and methods

To guide the initial phase of the research, descriptors in English such as "Aero Graphene," and "Graphene Aerogel" were selected and employed both individually and in binary combinations with terms such as "Aviation," "Aerospace," "Aircraft," "Lightweight," "Structural," "Thermal," "Conductivity," and "Vehicle." These terms were applied to the Web of Science database and, when necessary, supplemented with access to journals to obtain complete citations. The study adopts a qualitative-quantitative approach, aligned with the methodology described by [50]. Based on the selection of relevant sources from specialized scientific literature, the collected data were structured into formative content, emphasizing practical application for solving concrete problems and seeking viable solutions in the field of Engineering.

Regarding the filtering criteria applied to the search results previously described, five factors were used to formulate the textual corpus:

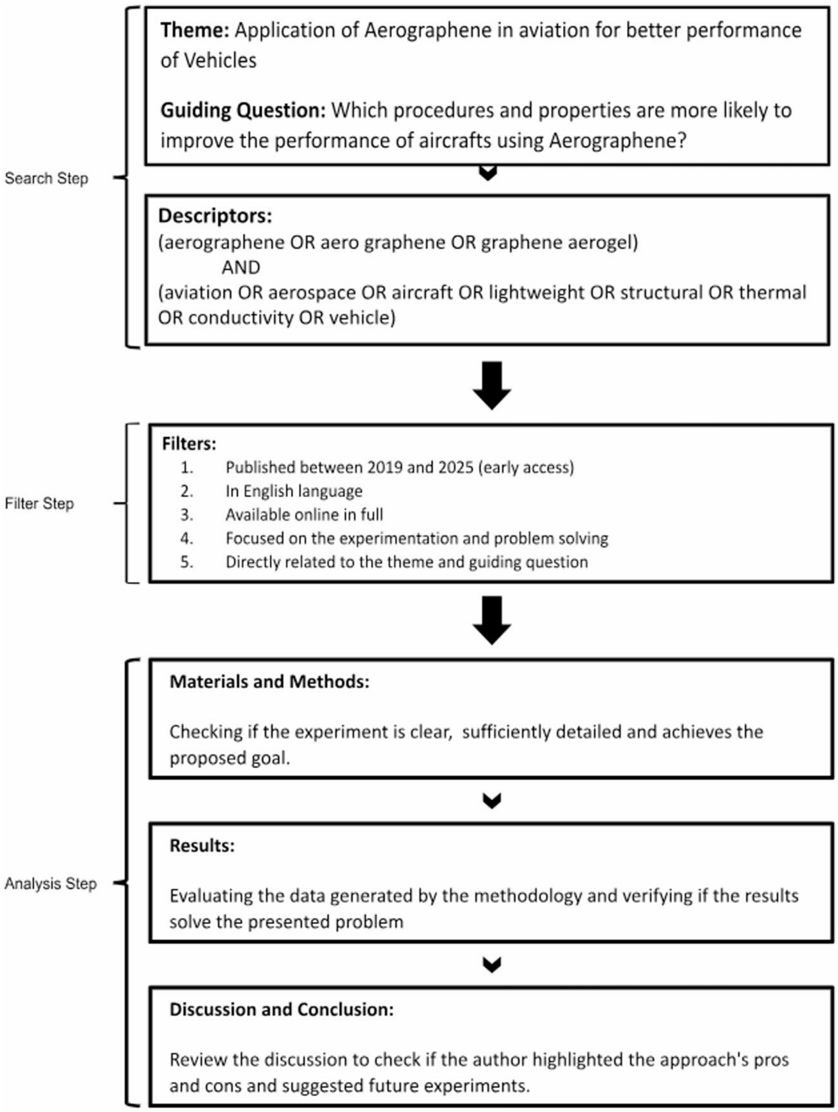
1. Publication timeframe between 2019 and 2025;
2. Publication language identified as English;
3. Articles classified as Open Access and available online;
4. Research described in the content of the work focused on experimentation and solution development;
5. Direct connection to the theme explored in this literature review.

2.1 Material inclusion criteria

The selection of studies for the textual corpus was guided by the central role of graphene aerogel in the reported material systems. Pure graphene aerogels and graphene-aerogel-based hybrids were included when graphene aerogel acted as the primary load-bearing, conductive, or insulating framework. Hybrid systems incorporating secondary phases, such as polymers, metal oxides, or ceramic components, were considered when these phases enhanced specific properties while preserving graphene aerogel as the dominant functional architecture. Aerogel materials not primarily based on graphene aerogel were included only as comparative references to benchmark aerospace-relevant properties and manufacturing approaches.

These filtering criteria are illustrated in the flowchart presented in Fig. 5, alongside the theme of the literature review and the guiding question for the development of the discussion.

Initially, 3,304 publications were retrieved using the search query on the Web of Science platform. By applying filters 1, 2, and 3, this number was reduced to a total of 523 articles published within the expected timeframe and available entirely in English online as Open Access. Further application of the filters, narrowing the research according to the type of publication and its content, reduced this number from 523 to 182 articles directly related to the central theme of the literature review. These 182 articles were analyzed in depth, as previously indicated in Fig. 5, resulting in a textual corpus of 22 articles. This progression in numbers and the adopted steps can be directly observed in the diagram presented in Fig. 6.



Theme: Application of Aerographene in aviation for better performance of Vehicles

Guiding Question: Which procedures and properties are more likely to improve the performance of aircrafts using Aerographene?

Descriptors:
(aerographene OR aero graphene OR graphene aerogel)
AND
(aviation OR aerospace OR aircraft OR lightweight OR structural OR thermal OR conductivity OR vehicle)

Filters:
1. Published between 2019 and 2025 (early access)
2. In English language
3. Available online in full
4. Focused on the experimentation and problem solving
5. Directly related to the theme and guiding question

Materials and Methods:

Checking if the experiment is clear, sufficiently detailed and achieves the proposed goal.

Results:

Evaluating the data generated by the methodology and verifying if the results solve the presented problem

Discussion and Conclusion:

Review the discussion to check if the author highlighted the approach's pros and cons and suggested future experiments.

Fig. 5 Formation of the textual corpus explained via flowchart

After the filtering process and the formation of the textual corpus, the selected studies were organized in Table 1 and its continuations according to the reported properties (**Properties**) and (**Aerospace Relevance**), manufacturing techniques (**Techniques**), types of aviation applications (**Application**), performance metrics (**Metrics**), and, finally, reported resistance and durability (**Durability**). Above-mentioned specifics were selected based on the key engineering parameters deemed crucial for aviation applications. Moreover, the research methodology emphasizes Graphene Aerogel material with the potential impact on aircraft performance, particularly in terms of weight reduction and structural integrity. The dataset was organized into categories such as properties, manufacturing techniques, applications, metrics, and durability (as summarized in Table 1) as these are critical parameters for aerospace applications.

Through the textual corpus, two analyses were conducted. The first involved a qualitative approach, exploring the capabilities of each reported material and how these translate into efficient applications for aviation use, highlighting the strengths and weaknesses

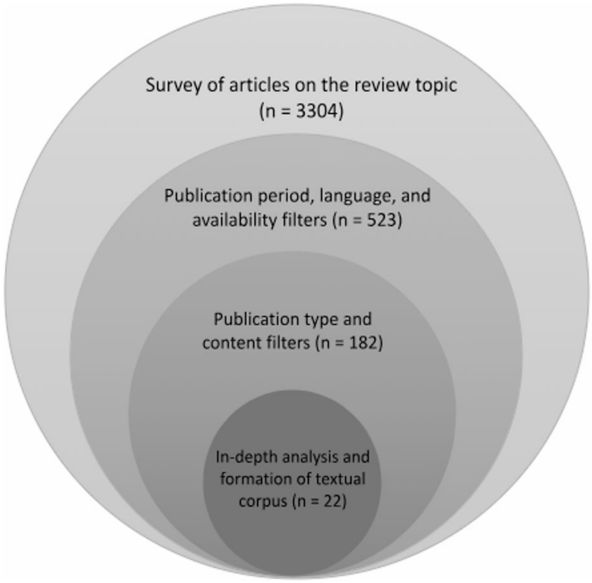


Fig. 6 Number of papers in each step of the filter process

of each study and material presented. The second analysis adopted a quantitative approach, numerically estimating the distributions of each column, identifying usage patterns, and determining how common each factor is in material production, directly correlating these findings with the aviation impacts identified in the first analysis. To reinforce both analyses, a bibliometric approach was employed, providing thematic connection graphs, word clouds, and term distribution charts, thereby enhancing visualization and enriching the discussion with factors that are challenging to observe solely through text and tables.

3 Results and discussion

Based on the data presented in Table 1 and its continuations, each column was analyzed in depth following the qualitative-quantitative logic previously discussed in the subsections of the results and discussion. Initially, the analysis aimed to demonstrate the peculiarities of each factor in the table and its impact on the problem's context. This was followed by a numerical analysis of the included studies, highlighting how each discussed factor is distributed across the corpus and identifying potential connections between them and prospective solutions.

3.1 Material properties of graphene aerogel and manufacturing

Where hybrid or comparative aerogel systems are discussed, they are used to highlight material design trends, processing strategies, and performance benchmarks that directly inform the development and optimization of Graphene Aerogel-based materials for aerospace applications.

The column (**Properties**) from Table 1 and its continuations highlights the primary strengths and limitations of Graphene Aerogel for aerospace applications. The aerogel is an ultralight material, with a density as low as 3.13 mg/cm3 [59], and features high porosity, which enhances fuel efficiency and increases payload capacity. Additionally, it exhibits excellent thermal insulation properties, ranging from 0.018 to 0.041 W/(mK)

Table 1 Organizing the literatures of the textual corpus according to their respective data collected during the in-depth analysis step

Properties	Aerospace Relevance	Techniques	Application	Performance Metrics	Mechanical Durability	References
Super-compressible, mechanically stable, low elastic modulus	Vibration tolerance, fatigue resistance, and deformation recovery for lightweight aerospace components	Hydrothermal Synthesis, Chemical Reduction and Freeze-drying	Wearable Devices	Sensitivity: 5.7 kPa^{-1}, detection limit: ~ 0.0055 kPa	98.7% stress retention, 98.1% height retention, 1000 compression cycles	[51]
Highly porous, Aligned hollow channel structure, Thin annular aerogel wall	Mass reduction, directional transport, and thermal management in aerospace systems	Chemical Reduction and Freeze Drying	Purification/ Filter Systems	Water evaporation rate of ~ 3.29 kg m^{-2} h^{-1} under 1 sun illumination	Excellent stability and salt rejection for seawater desalination	[52]
Highly porous, Integrated 3D framework, low thermal conductivity	Thermal insulation and surface temperature protection for aerospace structures	Sol–gel Method	Thermal Application	Causes 1185 K temperature drop on structure surface after 10 min heat exposure	Weight Loss only ~10% in TGA, good thermal stability	[53]
Highly porous, Lightweight, 3D interconnected network structure	Electromagnetic shielding and lightweight integration for avionics protection	Chemical Reduction	Electromagnetic Application	9.2 GHz bandwidth with reflection coefficient < -10dB	Excellent thermal stability, negligible volume change after heating	[54]
Highly porous, Interconnected graphene networks, adjustable porous structures	Energy storage capability and EMI shielding in multi-functional aerospace components	Chemical Reduction	Electromagnetic Application	Specific capacitance of 257.2 F g^{-1} for fructose-graphene aerogel at 10 mVs^{1}	Excellent stability after 5000 consecutive voltammogram cycles	[55]
Highly porous, Interconnected graphene networks, Ultralight, Flexible	Strain sensing, vibration monitoring, and structural health monitoring in aircraft	Freeze-drying and Thermal Annealing	Wearable Devices	Strain sensing 0.1–80%, pressure sensitivity ~10 kPa^{-1}, vibration sensing up to 4000 Hz	Excellent stability after > 1,000,000 vibration cycles, fire-resistant	[56]
Lightweight, Low thermal conductivity, High elasticity, Low thermal conductivity	Thermal insulation and mechanical compliance under aerospace operating conditions	Freeze-drying	Thermal Application	Thermal conductivity is as low as 0.026 W/mK	Fire-resistant, weight loss < 10% at 1000 °C	[57]

Table 1 (continued)

Properties	Aerospace Relevance	Techniques	Application	Performance Metrics	Mechanical Durability	References
Shape memory, Stimuli responsive, Low density, Anti- fatigue/wear, Anti-corrosion, Low thermal conductivity, Self-healing	Adaptive structures, damage tolerance, and extended service life in aerospace systems	Hydrothermal Synthesis	Structural Application	Shape recovery up to 98–99%, thermal activation at 120 °C, electro-actuation at 6-40 V	High sustainability impact resistance, thermal/shock/impact damage prevention	[58]
Ultralight, elastic, Low density, Low thermal conductivity	Pressure sensing and thermal insulation for lightweight aerospace applications	Freeze-drying and Thermal Annealing	Thermal Application	Compressive strength up to 4.98 kPa at 80% strain, pressure sensing range 0.044–0.92 kPa	Only 2.8% plastic de- formation after 500 compression cycles at 60% strain	[59]
Cross-linked lignin- based, Wood like texture, Aligned micro-sized pores, Low density *(non-GA aerogel; comparative reference)*	Lightweight filtration and environmental control applications in aerospace platforms	Freeze-drying and Thermal Annealing	Purification/ Filter Systems	Filtration efficiency > 99.9% for ultrafine particles, low pressure drop (45 Pa at 8 mm thickness)	Excellent mechanical stability, 98.7% stress retention after 1000 compression cycles	[60]
Ultralight, Porous, Tunable CNF derived carbon nanostructures *(non-GA aerogel; comparative reference)*	Microwave absorption and EMI mitigation in aerospace environments	Freeze-drying and Thermal Reduction	Electromagnetic Application	Effective absorption bandwidth of 6.16 GHz, minimum reflection loss of 66.3 dB at 2.14 mm thickness	High Chemical stability, excellent structural integrity	[61]
Low density, High surface area, Concentrated pore diameter distribution	Lightweight structural efficiency and multi-functional integration in aerospace design	Freeze-drying, Chemical Reduction	Electromagnetic Application and Thermal Application	Electrical conductivity of 1.49 S cm^{-1}, fracture strength of 0.79 MPa	98.7% stress retention and 98.1% height retention after 1000 compression cycles at 50% strain	[62]
Ultra porous, Interconnected hollow GaN micro tetrapod, Low wall thickness *(non-GA aerogel; comparative reference)*	Pressure sensing and robustness under extreme aerospace environments	Thermal Reduction	Structural Application	Nearly linear conductance vs pressure up to 40 atm, stable signal after ~10 s	Robust under strong accelerations, vibrations, radiation, aggressive chemicals, vacuum	[63]

Table 1 (continued)

Properties	Aerospace Relevance	Techniques	Application	Performance Metrics	Mechanical Durability	References
Ultralight, highly porous, mechanically robust, Low thermal conductivity, High sound absorption	Combined thermal insulation, acoustic damping, and lightweight structural performance	Freeze-drying	Electromagnetic Application and Thermal Application	Sound absorption coefficient of 0.72 (500–1500 Hz), thermal conductivity 0.0424 W/mK, density 6.51 kg/m^3	Energy loss coefficient of 29%, com- pressive strength of 5 kPa at 30% strain after 10 compressions cycles	[64]
Ultralight, highly porous, Face-to-face stacked structure, Low density	High-efficiency EMI shielding with minimal mass penalty in aircraft systems	Chemical Reduction and Thermal Annealing	Electromagnetic Application	EMI shielding effectiveness of 64.1 dB at 1 mm thickness, specific EMI SE of 173,243 dB cm^2 g^{-1}	Excellent stability under mechanical deformation, extreme temperatures, flame, underwater environments	[65]
Super compressible, mechanically stable, High porosity, Aligned hollow channel structure	Lightweight energy storage architectures and mechanical resilience in aerospace	Hydrothermal Synthesis, Freeze-drying and Nanoparticle Embedding	Structural Application	Potential lightweight energy storage for air- craft	Stable performance in ambient air for 500 cycles	[66]
Super-compressible, mechanically stable, Lightweight	Impact resistance and enhanced mechanical performance for aerostructures	Hydrothermal Synthesis, Chemical Reduction, Freeze- drying and Nanoparticle Embedding	Structural Application	37% increase in tensile strength, 55% increase in flexural strength, 56% increase in impact strength	98.7% stress retention, 98.1% height retention after 1000 compression cycles at 50% strain	[67]
Highly porous, 3D interconnected network, large surface area, Low density	Structural energy storage and multi-functional load-bearing components	Hydrothermal Synthesis, Chemical Reduction, Freeze- drying and Supercritical Drying	Structural Application	High specific capacity (> 1000 mAh/g), good rate capability, long cycle life	Excellent mechanical stability, ability to accommodate volume changes	[68]
Low density, High compression strength, Hydrophobic	Durable EMI shielding and environmental resistance in aerospace conditions	Freeze-drying and Chemical Reduction	Electromagnetic Application	EMI shielding effectiveness up to 87 dB at 2.0 mm thickness	Excellent stability and salt rejection for seawater desalination	[69]

Table 1 (continued)

Properties	Aerospace Relevance	Techniques	Application	Performance Metrics	Mechanical Durability	References
Highly porous, Integrated 3D framework, Superior photonic absorption, Low thermal conductivity	Solar-thermal conversion and multi-functional aerospace surface applications	Hydrothermal Synthesis, Chemical Reduction, Freeze-drying and Thermal Annealing	Structural Application and Purification/Filter System	Solar-thermal response of 169.7 °C temperature increased within 1 s, vapor generation efficiency of 89.4% at 10 sun illumination	98.7% stress retention, 98.1%height retention after 1000 compression cycles at 50% strain	[70]
Highly porous, Interconnected 3D net- work structure, Low density, electrically conductive	EMI shielding and electrical functionality for aerospace electronics protection	Chemical Reduction and Nanoparticle Embedding	Electromagnetic Application	EMI shielding effectiveness 20–30 dB, specific shielding effectiveness up to 1700 dB cm^3/g	98.7% stress retention, 98.1% height retention after 1000 compression cycles at 50% strain	[71]

To enhance clarity, material properties summarized in Table 1 are accompanied by brief functional descriptors indicating their relevance to aerospace structural, thermal, and electromagnetic performance requirements. Pure Graphene Aerogels refer to materials in which Graphene Aerogel forms the primary structural network. Graphene Aerogel-based hybrid systems denote aerogels where Graphene Aerogel remains the dominant framework while secondary phases are introduced to enhance specific functionalities. Non-Graphene Aerogel systems are included solely for comparative benchmarking of aerospace-relevant performance metrics. All numerical values reported in Table 1 were verified against the original publications to ensure accurate representation of material properties, performance metrics, and durability characteristics. Application categories and durability descriptors were assigned based on the primary focus and testing framework of each cited study

[53], robust durability under repeated stress, and exceptional electromagnetic shielding capabilities, achieving values of up to 87 dB [69].

Graphene Aerogel, is a revolutionary material with transformative potential for aviation, offering significant enhancements in aircraft performance through its unique properties.

3.1.1 Weight reduction and structural efficiency

3.1.1.1 Lightweight nature As one of the lightest materials, Graphene Aerogel can drastically reduce aircraft weight, leading to improved fuel efficiency, extended range, and increased payload capacity [72].

3.1.1.2 Strength-to-weight ratio Its integration into composites could sur- pass traditional materials like carbon fiber, enabling lighter yet stronger airframes, wings, and fuselage components, potentially allowing innovative design modifications (e.g., larger windows) [73].

3.1.2 Thermal management

Despite graphene's high thermal conductivity, aerogel's porous structure offers insulating properties. This duality allows for tailored applications-managing heat in engines/electronics or insulating cryogenic fuel systems (e.g., liquid hydrogen storage) [74].

3.1.3 Electrical conductivity and avionics

Graphene's conductivity can improve avionics, sensors, and electromagnetic shielding, boosting communication reliability and reducing electrical system weight [5, 75].

3.1.4 Noise and vibration damping

The material's porosity aids in sound absorption, reducing cabin noise. Its structure may also dampen vibrations, enhancing passenger comfort and structural longevity [76].

Graphene Aerogel holds promise to revolutionize aviation through weight savings, thermal and electrical enhancements, noise reduction, driving efficiency and sustainability. However, realizing its full potential requires addressing production challenges, safety certification, and lifecycle sustainability. As research progresses, Graphene Aerogel could become a cornerstone of future aviation advancements [77].

These factors were confirmed through the quantitative analysis of the same column, with over 50% of the work reporting the reduced weight characteristic, either through direct weight measurements or density data. Specifically, 12 out of the 21 papers in the textual corpus provided such data. Regarding porosity and thermal conductivity, both are directly related and were identified as advantageous material properties in a total of 16 studies presented in Table 1 and its continuations, representing over 70% of the studies analyzed in this review. Observing Fig. 7, it is evident that there is a significant overlap between these two groups of reported properties, with 11 publications emphasizing both characteristics simultaneously. This accounts for exactly half of the textual corpus and, consequently, further reinforces the benefits of the material for the application under investigation in this review.

Nevertheless, challenges remain, including its fragility under extreme mechanical loads and scalability limitations due to complex manufacturing techniques, such as freeze-drying. These processes often involve significant environmental concerns, stemming from energy-intensive operations or the use of non-renewable precursors. Despite these challenges, Graphene Aerogel holds considerable promise for advancing ultralight, efficient, and eco-friendly technologies in the aviation industry. According to the column (**Techniques**), which highlights the preferred manufacturing methods chosen in each study, processes such as freeze-drying, chemical reductions, and hydrothermal synthesis were identified as having significant potential for large-scale production in the aviation sector.

However, energy-intensive processes like freeze-drying or thermal annealing may contribute to increased carbon emissions unless production methods are optimized for efficiency. While hydrothermal synthesis produces strong and flexible aerogels suitable for

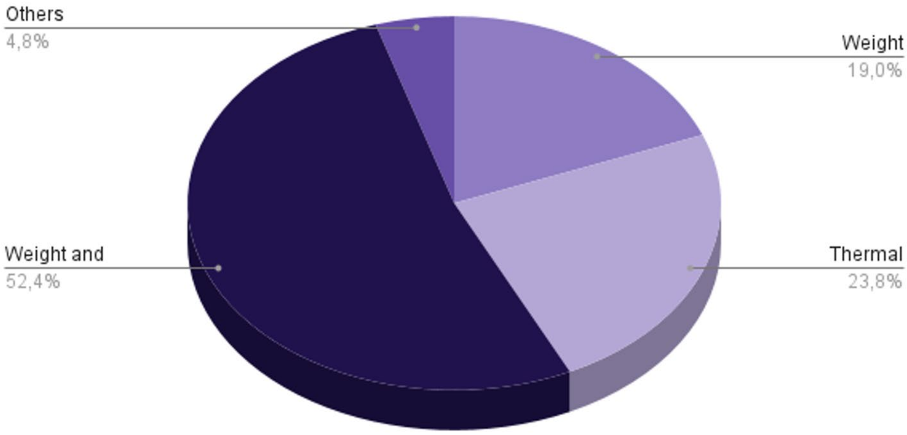


Fig. 7 Distribution of reported Material Properties across the textual corpus

structural components in aviation, thermal annealing enhances fireproofing and stability, making it a critical process for developing advanced aviation technologies.

Through a numerical analysis of the presented data, the notable popularity of the Freeze-drying method becomes evident, as it was employed in 14 of the publications selected for this review, representing approximately 66.7% of them. This method was utilized either as the sole technique or as part of a set of techniques to achieve the final result, thereby confirming the substantial production potential previously highlighted in this discussion. Reinforcing this potential, the data graphically presented in Fig. 8 illustrate the overwhelming popularity of the Freeze-drying method among the reported experiments. The remaining groups represent the primary focuses of manufacturing techniques employed when Freeze-drying was not utilized.

3.2 Performance metrics and impacts of graphene aerogel in aviation

Graphene Aerogel exhibits a remarkable potential to revolutionize the aviation industry by offering lightweight, resilient, and multifunctional materials tailored for diverse applications. Its extremely low weight and high porosity make it ideal for minimizing aircraft mass, directly enhancing fuel economy and payload capacities. Moreover, its thermal insulation properties enable it to meet the rigorous demands of high-temperature environments, such as engine components or spacecraft exteriors, ensuring both safety and functionality under extreme conditions. The fabrication methods employed to produce Graphene Aerogel, including freeze-drying, chemical reduction, and hydrothermal synthesis, significantly influence its properties and suitability for specific applications. For instance, chemically reduced aerogels with high electrical conductivity are particularly advantageous for electromagnetic interference (EMI) shielding, a critical requirement in modern aircraft to protect sensitive electronic systems [26, 78–80].

Graphene Aerogel metrics are typically calculated based on key material properties such as density, porosity, thermal conductivity, electrical conductivity, mechanical strength, and electromagnetic interference (EMI) shielding. These metrics align with standard aerospace material measurements to ensure compatibility with industry benchmarks.

Density & Porosity Graphene Aerogel's density is as low as 3.13 mg/cm^3, making it one of the lightest materials ever developed. Standard aerospace materials, such as carbon

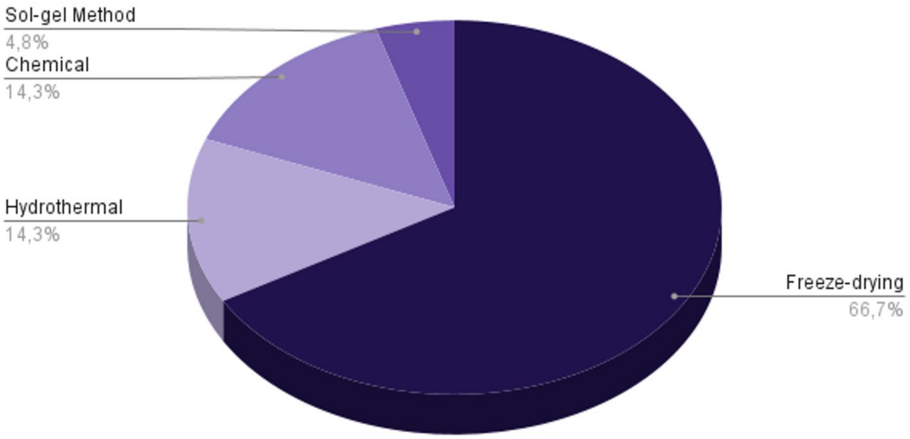


Fig. 8 Distribution of reported Manufacturing Techniques across the textual corpus

fiber composites, have significantly higher densities. The low density directly enhances fuel efficiency and increases payload capacity by reducing overall aircraft weight [59].

Thermal Conductivity Graphene Aerogel exhibits ultra-low thermal conductivity, ranging between 0.018 and 0.041 W/mK. This surpasses many conventional aerospace insulation materials, enabling better heat management in aircraft structures, engine compartments, and spacecraft exteriors [53].

Mechanical Strength Despite its low weight, Graphene Aerogel demonstrates high compressive strength retention (98.7%) and durability under repeated stress. This ensures longevity in aerospace applications while maintaining structural integrity.

Electromagnetic Shielding (EMI SE) With EMI shielding effectiveness reaching up to 87 dB at 2.0 mm thickness, Graphene Aerogel significantly outperforms traditional shielding materials. This is critical for protecting avionics and communication systems from electromagnetic interference, enhancing aircraft reliability [69].

By replacing conventional materials with Graphene Aerogel, aviation benefits from the following improvements:

- *Increased Fuel Efficiency*: Due to extreme lightweight properties.
- *Enhanced Structural Durability*: High mechanical strength and impact resistance.
- *Better Thermal Insulation*: Improved performance in high-temperature environments.
- *Superior EMI Protection*: Ensuring safety and functionality of electronic systems.

These improvements make Graphene Aerogel a game-changer in aviation, beyond its functional versatility, metrics such as durability underscores its suitability for long-term use in demanding aviation environments, as highlighted in studies summarized in Table 1 and its continuations. Its resistance to mechanical stress, thermal cycling, and environmental degradation ensures reliability under harsh operating conditions. The material's unique combination of lightweight design, multifunctionality, and performance metrics, such as compressive strength, thermal stability, and EMI shielding effectiveness, positions it as a standout candidate for structural components, thermal protective layers, and avionics shielding. The interplay between these metrics and impact resistance is particularly significant, as advanced manufacturing techniques, such as freeze-drying and chemical reduction, enable precise control over the material's properties to meet stringent performance requirements. Furthermore, optimizing fabrication processes to reduce energy consumption and environmental impact will be crucial for aligning Graphene Aerogel development with broader sustainability goals, ensuring its role as a transformative material in the aviation sector.

These factors are even more notable when observing the word cloud generated from the terms present in the keywords and titles of the papers that composed the textual corpus of this discussion. Figure 9 represents this cloud, and from it, it is possible to discern the significance of weight and conductivity characteristics in the field of Graphene Aerogel. This is particularly true in the context of aviation, where the extremely light weight characteristic, without compromising other physical properties, is of paramount importance for the overall efficiency of the vehicle's operation.

Regarding the relevance of the topic in general, one can refer to Fig. 10, which organizes the main thematic groups present in the analyzed and discussed articles according to the factors of "Density" and "Centrality." The former refers to the raw number of

Fig. 9 Word Cloud from the most important terms in keywords, titles and abstracts from textual corpus publications

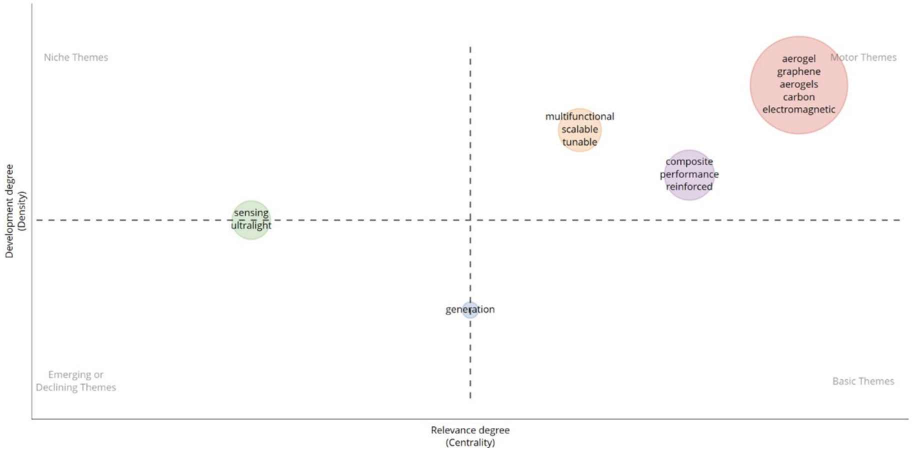


Fig. 10 Themes mapped and classified according to the number of papers published and the overall impact of the publications

publications from various sources, while the latter indicates the overall impact of the theme cluster based on the average of the publications included in that cluster. Through this mapping, it is once again possible to observe how the application of Graphene Aerogel, generally represented by the red cluster, is considered of significant importance, classified as a driving theme for the evaluated works.

Similarly, the purple cluster, which focuses on application performance, can be evaluated. Although it has shown increasing density over the years under study, it still does not have as much impact as the main cluster. Exhibiting the same behavior, but with reversed factors, is the green cluster, which represents studies related to the material's weight. Over the years, this theme has been gaining more impact in terms of publication influence; however, it still does not have sufficient volume to be considered a driving force like the red or purple clusters.

This distribution can also be observed by analyzing the thematic connection graph through clusters presented in Fig. 11, where each term is represented by a circle. The more relevant a term is to the overall set, the larger its representation. Its color is assigned based on the connections it has with other terms within its group, following the same color scheme as in Fig. 10 for clearer visualization.

Through this figure, the impact of the red group on the others is once again confirmed, with a clear visualization of how it connects with all the other groups. Additionally, it is evident that the green and purple clusters, previously discussed, have strong connections with the red group and also exhibit connections between each other. This allows for the inference that, for future works and the development of innovative solutions, a greater focus on the interaction and application of Graphene Aerogel for reducing vehicle weight while maintaining thermal and structural properties, in favor of performance enhancement, could lead to potential new high-performance solutions.

In this context of thematic analysis, it became evident how European and Asian governments are concerned with the overall theme of this review. The visual representation of the studies developed by the countries that formed the textual corpus can be observed in Fig. 12, where China's leadership in this area is apparent, with the country addressing nearly all the major themes related to Graphene Aerogel be it directly or indirectly. This influence extends beyond the textual corpus; by analyzing the most cited countries in the 21 works reviewed, China's dominance in the overall scenario is once again evident, as shown by Fig. 13.

4 Conclusions

This comprehensive review on the use of universal carbon molecule Graphene Aerogel in the aviation industry highlights the transformative potential. Through a detailed analysis of Graphene Aerogel's properties, fabrication techniques, and applications, it has

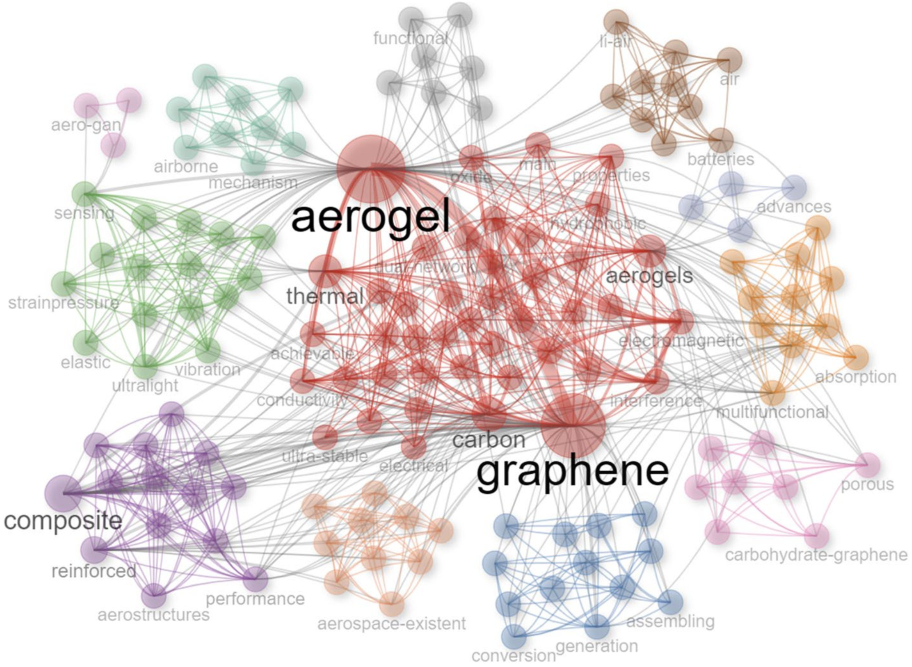


Fig. 11 Themes grouped and connected based on their interactions within the textual corpus

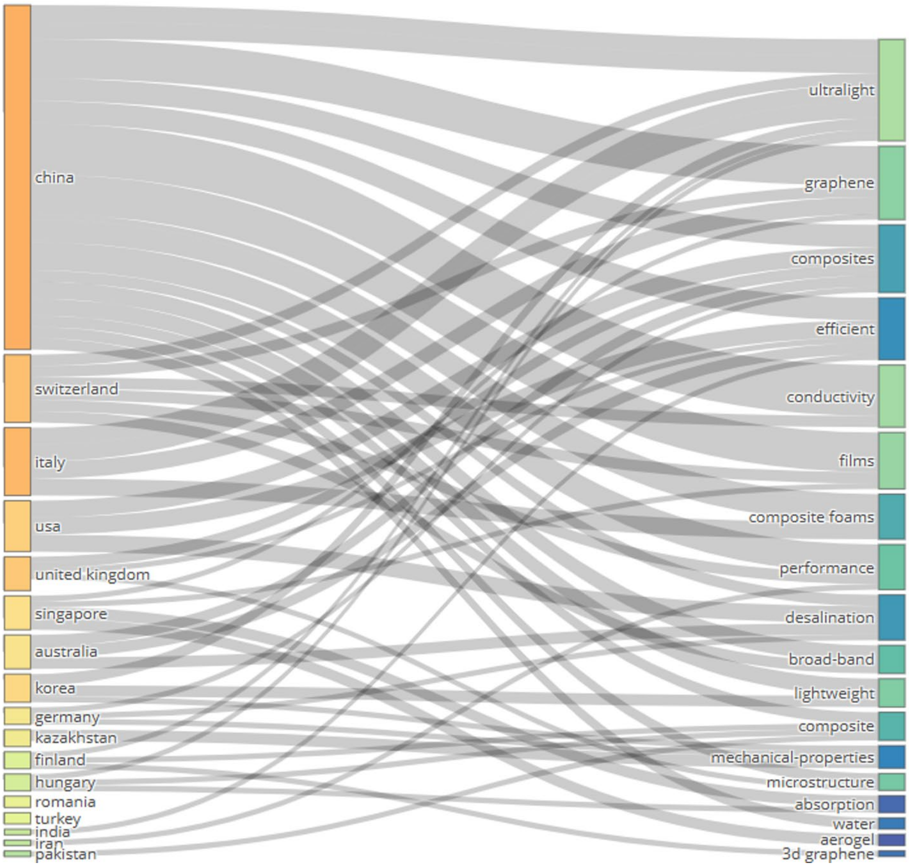


Fig. 12 Visualization of the impact of each major contributing country on the development of the graphene aerogel theme

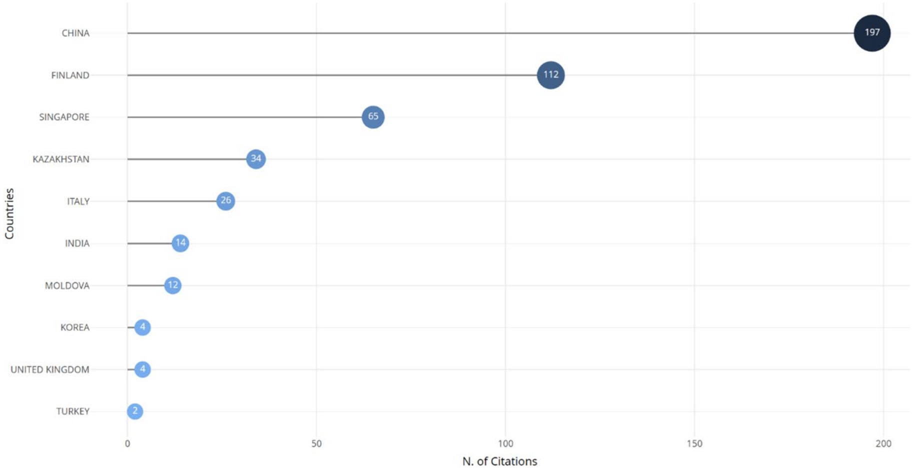


Fig. 13 Countries ranked by the number of citations from papers within the textual corpus

become evident that this material offers significant advantages in terms of weight reduction, thermal insulation, and electromagnetic shielding. This structure allows the reader to have a clear and systematic comparison of different Graphene Aerogel in formulations and their suitability for the aviation industry. However, current challenges related to large-scale production, durability, and environmental impact require continued attention from the scientific community and aviation industry.

The qualitative and quantitative analyses conducted in this study have revealed important patterns in current Graphene Aerogel research, highlighting promising areas for future development. To advance the development and application of Graphene Aerogel in aviation, the following steps are recommended:

- *Enhance Fabrication Techniques*: Focus on refining manufacturing processes, such as freeze-drying methods, to improve scalability and cost-efficiency.
- *Improve Material Strength*: Prioritize research on enhancing the mechanical durability of Graphene Aerogel to ensure its reliability under extreme conditions.
- *Reduce Environmental Impact*: Minimize the ecological footprint of Graphene Aerogel production to align with sustainability goals in aviation.
- *Foster Collaboration*: Promote international and interdisciplinary partnerships to accelerate innovation and streamline the path to real-world applications.

With continued research, Graphene Aerogel has the potential to revolutionize the aviation industry, paving the way for lighter, more efficient, and environmentally sustainable aircraft.

5 Future aspects

Future research on Graphene Aerogel for aerospace applications should focus on addressing the key limitations identified in this review through targeted and actionable strategies. One critical direction involves enhancing the mechanical robustness of Graphene Aerogel under extreme loading and fatigue conditions. This can be achieved through the development of reinforced graphene aerogel architectures, hybridization with polymers or ceramic phases, and bio-inspired structural designs that improve load distribution while preserving low density.

Scaling-up production remains another major challenge for the adoption of Graphene Aerogel in aerospace systems. Future efforts should prioritize scalable and reproducible fabrication routes, such as extrusion-based additive manufacturing, ambient-pressure drying, and continuous processing techniques, to reduce reliance on energy-intensive methods like freeze-drying. Process standardization and quality control protocols will be essential to ensure consistency of material properties at industrial scale.

Environmental sustainability should also be a central focus of future research. The use of renewable precursors, water-based processing routes, and low-temperature synthesis methods can significantly reduce the environmental footprint of Graphene Aerogel production. Life-cycle assessment studies are needed to evaluate environmental impacts from raw material sourcing to end-of-life disposal, particularly in the context of large-scale aerospace deployment.

From an application perspective, advancing Graphene Aerogel toward higher technology readiness levels will require comprehensive testing under realistic aerospace operating conditions, including thermal cycling, vibration, radiation exposure, and long-term mechanical fatigue. Integration of multifunctional capabilities, such as structural energy storage, embedded sensing, and electromagnetic shielding, should be pursued to maximize performance benefits without increasing structural mass.

Overall, by combining mechanical reinforcement, scalable manufacturing, and sustainability-driven design, Graphene Aerogel has the potential to evolve from a laboratory-scale material into a viable solution for next-generation aerospace structures.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

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The authors declare no competing interests.

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