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Graphene's Frontier in aerospace: current applications, challenges, and future directions for space engineering

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Graphene is suitable for aerospace and space engineering because its single carbon layer exhibits excellent mechanical, electrical and thermal characteristics. Its tensile strength, which exceeds that of steel by 100 times, together with its high conductivity and thermal stability position graphene as an effective performance booster for spacecraft systems. Herein, we examine how graphene serves different space-based functions, starting with reinforcement supports and moving to thermal applications and radiative safety, before investigating energy storage methods. Since graphene has a very low weight, it serves as an excellent material to lower spacecraft weight, which consequently enhances fuel consumption and payload transportation. Graphene shows unique advantages by supporting composite structures and controlling heat in critical systems to adapt to the complex operating conditions in space. Graphene-based power systems, ranging from supercapacitors to batteries, provide high stored energy and long battery life for long space missions. However, many barriers slow the progress of graphene, including the production of large amounts at low cost with stability under harsh space conditions. Scientists are exploring ways to tackle the challenges associated with graphene while incorporating composite materials to design better spacecraft. Space exploration will progress further because improvements in graphene technology have created better spacecraft materials that resist damage.

1. Introduction

Graphene, which is a sheet of hexagonally arranged carbon atoms, has been recognized as one of the most promising materials for high-performance applications. Graphene, which was first discovered in 2004, is firmer than steel (130 GPa), yet it is exceptionally flexible and featherlight. It also has a very high thermal conductivity of >5000 W m^{-1} K^{-1} and high electrical conductivity, which make it suitable for use in various industries, including electronics, energy storage, and aerospace.[1,2] By applying materials and coatings to aerospace and space exploration, parts and components can be exposed to radiation, micrometeoroid impacts, temperature variations, and vacuum. Therefore, the required performances are difficult to achieve using conventional materials, especially in terms of light weight, heat dissipation and durability. Among all material options, graphene has high specific strength, low density, as well as efficient thermal and electrical conductivity that would fit space applications. Of these applications, the possibility of using it as a reinforcement material in composite structures could transform the design of spacecraft, improving their strength and performance.[3–5]

Consequently, numerous challenges are experienced during space missions that design and require enhanced materials to increase the reliability and performance of spacecraft. Space also prevents the utilization of normal types of lubricants and coolants, which are indispensable for regulating heat in electronic and mechanical gears. Furthermore, spacecraft is a rocket placed in space where it is exposed to high energy cosmic radiation and micrometeoroids, which can lead to hardware wear and damage. These problems call for lightweight, high-performance, and durable materials for use in the construction of spacecraft since the mass of the manufactured spacecraft must be less than 3000 kg.[6–8] Based on the above

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challenges, graphene has the right attributes that are suitable for solving them. Owing to its high thermal conductivity, it is used as a heat spreader so that critical systems do not overheat. Additionally, its mechanical characteristics may improve spacecraft impact protection from micrometeoroids. Further, examining its radiation shielding properties reveals that graphene is suitable for shielding both spacecraft and astronauts from potentially damaging cosmic rays in long term space missions[9] and further several methods to achieve *in situ* preparation of high-performance graphene aerogels as multifunctional structural materials in aircraft, high-speed trains, or even buildings for the targets of energy efficiency, comfort, and safety.[10,11]

This review provides an overview of the use of graphene technology in the area of space exploration majoring in structures, heat dissipation, radiation protection, and electronics. Based on the present developments in the use of graphene-based materials and their applications in aerospace structures, we discuss and explain why graphene outperforms conventional materials. This paper also identifies difficulties in scaling up graphene manufacturing and its integration into composite structures and future research prospects for the deployment of graphene in aerospace applications. The aerospace community can take advantage of the properties of graphene to reduce the mass of spacecraft while simultaneously improving their strength and reliability under harsh conditions. Exploration of off-Earth environments is gradually becoming crucial in modern society, and the increased adaptability of graphene is a driving factor for the success of such missions.

2. Key challenges and requirements of space materials

Depending on the orbit in which the products are positioned, space material requirements can be very strict. Every orbit is different and has different environmental issues, including temperature fluctuations and radiation, meteorite impacts by micrometeoroids, and atomic oxygen deterioration. These are outlined in the table below, including weight considerations, emphasizing the need to use light, strong, and very hard materials that can sustain the conditions inside the spacecraft for long periods without degrading the spacecraft's performance (Table 1). Orbital environments are diverse and extreme; therefore, spacecraft requires materials that can effectively handle these conditions. In the LEO, at altitudes from 160 to 2000 km, materials face several challenges, such as exposure to atomic oxygen, high radiation, micrometeoroids, and temperature variation from −70 to 150 degrees Celsius. To survive

Table 1 Key environmental challenges and requirements for materials[16–19]

Orbit type and altitude range	Key environmental challenges	Requirements for materials
Low earth orbit (LEO) 160–2000 km	- Atomic oxygen exposure	- Corrosion resistance against atomic oxygen
	- High radiation	- Radiation shielding
	- Micrometeoroids	- Thermal stability
	- Temperature fluctuations (−70 °C to 150 °C)	- Impact resistance
Medium earth orbit (MEO) 2000–35 786 km	- Increased radiation	- Radiation resistance due to prolonged exposure
	- Micrometeoroid impacts	- High mechanical strength
	- Temperature variation	- Thermal management to cope with temperature shifts
Geostationary orbit (GEO) ∼35 786 km	- Intense solar radiation	- UV radiation resistance
	- Temperature extremes (−170 °C to 120 °C)	- Thermal conductivity and insulation
	- High vacuum	- Low outgassing materials
High earth orbit (HEO) above 35 786 km	- High cosmic radiation	- Radiation shielding from cosmic rays
	- Vacuum	- Low outgassing materials
	- Micrometeoroid impacts	- Impact resistance for micrometeoroids
Polar orbit (∼200–1000 km)	- Extreme temperature cycles	- Temperature resistance to wide swings (−150 °C to 300 °C)
	- High radiation exposure	- Radiation protection
	- Atomic oxygen	- Corrosion resistance
Sun-synchronous orbit 600–800 km	- Constant solar exposure	- UV and thermal radiation resistance
	- Temperature cycles (−150 °C to 150 °C)	- Lightweight materials for efficiency
	- Atomic oxygen	- Thermal stability
Lunar orbit 100–1000 km around the moon	- Extreme temperature swings (−150 °C to 120 °C)	- Thermal management for extreme fluctuations
	- Micrometeoroid impact	- Impact resistance
	- Solar radiation	- Radiation protection
	- Intense cosmic radiation	- Radiation shielding
Interplanetary space beyond Earth's orbit	- Temperature extremes (−250 °C to 200 °C)	- Extreme thermal resistance
	- High vacuum	- Long-term durability for long missions
Deep space far beyond planetary orbits	- High cosmic radiation	- Radiation protection
	- Extreme cold (<−200 °C)	- Thermal insulation
	- Vacuum	- Low density for weight efficiency

these conditions, few requirements must be fulfilled: they must possess corrosion-resistant protection from atomic oxygen, radiation, heat stability and shielding from the impact of micrometeoroids.[12] In the MEO, with altitudes ranging from 2000 to 35 786 km, the harshness conditions found are radiation and micrometeoroid impacts and temperatures. Products in MEO should be made to withstand long radiations, be strong mechanically for shock absorptions and also capable of managing high temperatures.[13]

A high GEO at approximately 35 786 km comes with many challenges, including high solar radiation, extreme temperatures ranging from −1700 °C to 120 °C and vacuum. Here, materials should be environmentally stable, that is they should be able to withstand UV radiation, should have high thermal-o-thermal conductivity and good insulating properties and should not outgas in the vacuum of space. Similar to MEO, the High Earth Orbit that is beyond 35 786 km presents dangers of exposure to cosmic radiation, vacuum and micrometeoroids. The materials used in this region must therefore offer high protection from cosmic radiation, materials with low rates of outgassing and high impact resistance.[14] Polar orbits in the range of 200–1000 km indicate a very high thermal cycling, radiation and atomic oxygen environment and therefore require metals that have high temperature stability that can withstand temperatures from −150 °C to +300 °C, radiation tolerance and atomic oxygen corrosion. Such orbits, which range from 600 to 800 kilometers altitudes of sun synchronous orbit, are exposed to constant solar radiation and temperature variations ranging from −1500 °C to +1500 °C and atomic oxygen. Such materials require resistance to UV and thermal radiation, low density for optimal performance, and thermal stability under continuous environmental loading.[15] From 100 to 1000 km in the lunar orbit, extreme conditions, such as temperature variations ranging from – 150 to 120 Celsius, micrometeorite impacts, and powerful solar radiation, are dangerous for the materials. This orbit requires additional shielding for wide heat shock changes and stringent radiation tolerance besides the well-known impact protection for the used materials.

Again, there are areas outside the Earth's orbit, including extra-terrestrial matter, intense cosmic radiation, extremely low temperatures ranging from −2500 K to 2000 K and high vacuum such that the materials utilized have to give good protection from radiation, excellent thermal stability and durability for longer ages for more elaborate space missions. Finally, in extended space, the material far beyond the planetary systems experiences high radiation cos beyond the magnetosphere, a VACS temperature below −200 °C and severe vacuum. Radiation shielding, thermal insulation, lightweight, and high strength are some of the characteristics that advanced materials ideal for long-duration space missions must possess. Every orbit requires components that have endurance when subjected to conditions such as radiation, corrosion, temperature changes and other impacts, including micrometeoroids, aluminum alloys, and carbon fiber composites, and BNNTs can satisfy such requirements because they are light, strong, and efficient for spacecraft constructions. The proper material selection is critical to future space voyages, as the desired elements need to be both safe, efficient and cost effective in various orbits.[16–19]

3. Graphene's unique properties applied to space

Graphene is a two-dimensional material; it is a monolayer of carbon atoms arranged in a hexagonal lattice or a hexagonal planar lattice known as a honeycomb lattice. In graphene, every carbon atom is connected to the three nearest carbon atoms through powerful covalent connections to provide a two-dimensional planar structure in which all carbon atoms are sp^2 hybridized. This bonding structure confers on graphene its mechanical stiffness, electrical conductivity and thermal coefficients of expansion. In graphene, carbon atoms are linked using sigma (σ) bonds strengthening the in-plane plane; the unhybridized p-orbitals create pi (π) bonds existing in the plane above and below the graphene plane. Thus, these π-electrons are free to move over the entire sheet and possess high mobility, which gives the graphene highly efficient electrical conductivity. These delocalized electrons also make a significant contribution to the recognition of graphene, including in thermal conductivity and mechanical status.[20,21]

The layering of graphene, as illustrated in Fig. 1, is limited to a single atom thick because it is a two-dimensional material, and thinness facilitates the basic characteristics of transparency, flexibility, and light weight moments. Graphene is also two dimensional, with a high surface area achievable and considerable chemical activity likely at the edges of the lattice, at which imperfections or groups can be incorporated to suit particular uses. This basic set of properties owing to the graphene structure—atomic thickness, high mechanical strength, flexibility, electron conductivity and chemical stability—makes graphene a material perspective for future advanced technologies, including the space industry, where high-performance material can withstand extreme conditions and maintain minimum weight and high functionality. The last few sections focus on the mechanical, thermal, electrical and barrier characteristics of graphene, which are its most striking features.[22,23]

3.1. Mechanical strength

Another surprising characteristic of graphene is its approachability, which indicates its mechanical strength. Graphene shows remarkable strength at 130 GPa, surpassing steel by more than 100 times and creating value for aerospace manufacturing. This low-density feature enables lighter weight production. In space programs, by far the best advantage is the high strength-to-weight ratio, which is very important for the reduction of spacecraft and satellite mass; literally, every kilogram saved leads to the kilograms of fuel saved and the extra kilograms of payload. This is why this property is especially valuable for the creation of light-weight structural materials with high durability and impact personalities, which are indispensable under conditions of sharp interference and mechanical loading during a start and flight, in particular, in protection from micrometeorite impacts.

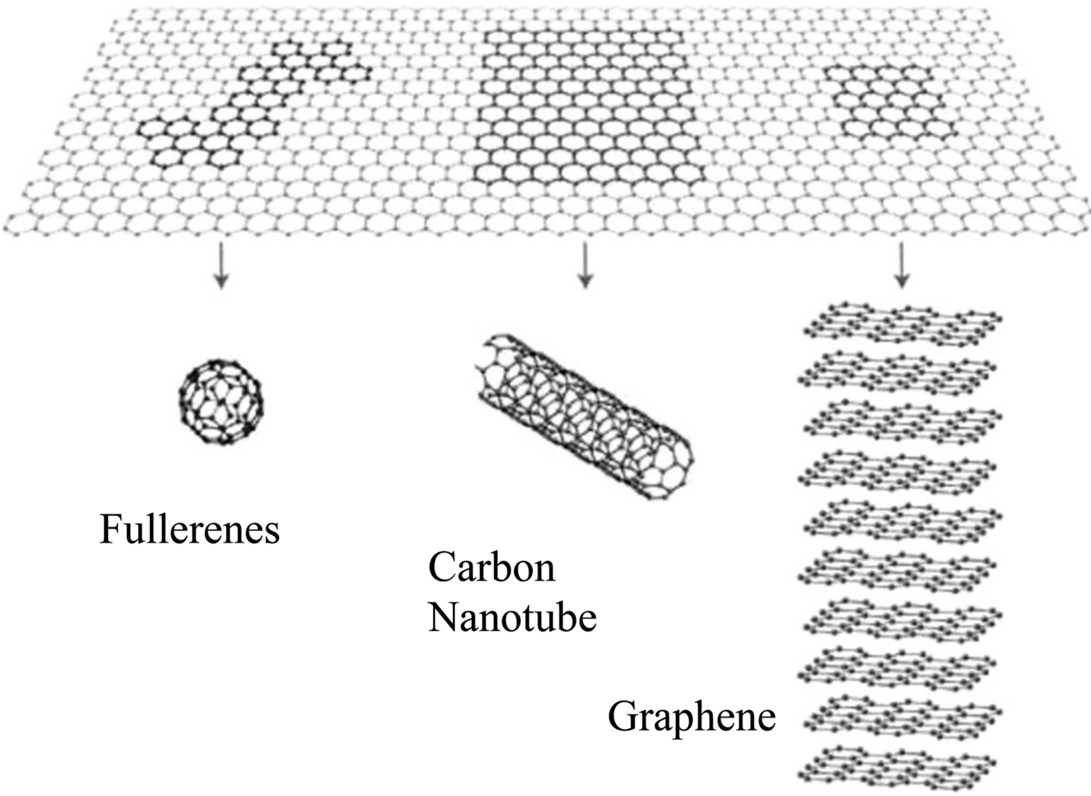

Fig. 1 Single atomic layer graphene, carbon nanotube and fullerenes.[22]

Table 2 lists the tensile strength, density, and strength-to-weight ratio of some of the materials utilized for aerospace and space engineering applications. Graphene displays an excellent tensile strength of 130 GPa and a density of 0.0023 g cm^{-3}, the unique strength to weight ratios could be useful as a material in space applications because it is both lightweight and incredibly strong. Steel with a tensile strength of 1.3–2.0 GPa and a higher density of 7.85 g cm^{-3} has a moderate strength-to-weight ratio. Aluminium alloy (6061-T6) has fewer strength-to-weight ratios, and its tensile strength is as low as 0.3–0.4 GPa. Titanium alloy (Ti-6Al-4V) has a comparatively better strength of 0.9–1.1 GPa and a density of 4.43 g cm^{-3} but has high strength as an aerospace part. Carbon fiber composites have a tensile strength of 3.5–6.0 GPa but with a lower density of only 1.75 g cm^{-3}, so are efficient in terms of strength/density. Kevlar, which is designed to possess high impact resistance, has a tensile strength of 3.6–4.0 GPa, while its density is 1.44 g cm^{-3}. Magnesium alloy (AZ31) has a much lower tensile strength of 0.2–0.3 GPa. However, it is light with a very low density of 1.78 g cm^{-3}. In general, real-world applications highlight graphene as the material of choice for space-based technologies requiring advanced materials.

3.2 Thermal conductivity

New materials, such as graphene, feature extremely high thermal conductivity, more than 5000 W m^{-1} K^{-1}, which is significantly higher than those of copper and aluminum, and are widely used in thermal control systems. In an extreme space environment where high and low ranges fluctuate significantly and thermal dissipation issues occur frequently, the possibility of using graphene for heating and cooling important electrical

Table 2 Comparison of the tensile strength and density properties of graphene with those of other space grade materials

Material	Tensile strength (GPa)	Density (g cm^{-3})	Strength-to-weight ratio	Ref.
Graphene	130	0.0023	Extremely high	24
Steel (aerospace grade)	1.3–2.0	7.85	Moderate	25
Aluminum alloy (6061-T6)	0.3–0.4	2.70	Low	26
Titanium alloy (Ti-6Al-4V)	0.9–1.1	4.43	High	27
Carbon fiber (composites)	3.5–6.0	1.75	Very high	28
Kevlar (aramid fiber)	3.6–4.0	1.44	High	29
Magnesium alloy (AZ31)	0.2–0.3	1.78	Low	30

devices and batteries at space stations appears relatively promising. Moreover, the thermal properties of graphene are ideal for improving solar panel operations in satellites, where proper heat dissipation can significantly increase lifetime application efficiency.

The thermal conductivity materials often used in space are illustrated in Table 3. The thermal conductivity of graphene is 3000–5000 W m^{-1} K^{-1}, and it is highly suitable in thermal management for electronics and solar panels because it has excellent thermal conduction properties with high heat spreading. Although substances with low TC include copper and silver, with TC of 390–400 W m^{-1} K^{-1} and TC of 420–430 W m^{-1} K^{-1}, respectively, they are used in electrical wires as conductors, heat sinks and exchangers. Aluminum is in the middling range of thermal conductivity (167–218 W m^{-1} K^{-1}) and acts as both the structural and heat control element in satellites; titanium alloys are much less thermally conductive (6.7–7.0 W m^{-1} K^{-1}) and are used where light, heat-shielded sections are needed. Carbon fiber composites (10–200 W m^{-1} K^{-1}) are versatile but good examples of poor thermal conduction materials, an ideal feature for heat shields. Composites of beryllium provide a good weight-to-thermal-conductivity ratio, and silicon carbide (120–270 W m^{-1} K^{-1}) is used often in the application of space mirrors and heat shields. The super high thermal conductivity of graphene enhances its functionality as a very high-level thermal interface material for space applications. Another property of graphene, thermal conductivity, is a massive benefit because heat management is crucial in space environments where a vacuum is present. In satellite panels and heat dissipation applications, this material is best because it does not add much weight to the system while removing heat.

3.3 Electrical conductivity

Graphene is more conductive than many metals because it possesses electron mobility at greater than 200 000 cm^2 V^{-1} s^{-1} at room temperature. This makes it very suitable for use in space borne electronic applications, such as antennas, communication systems and sensors. In satellites and spacecraft, it is possible to have even faster signal transfer along with higher efficiency in energy transfer in electronic components, which must cut down the overall energy consumption. In addition, graphene must be electrified to achieve conductivity, and this conductivity is maintained in the absence of air, that is in the outer space environment, thereby opening up the opportunity of constructing radiation-resistant electronics with little or no deterioration in their use of graphene.

Table 4 shows the electrical conductivity of materials commonly used in the space industry. Graphene is the most conductive with a conductivity estimated to be about $\sim 1 \times 10^8$ S m^{-1}, thus making it excellent in high-speed electronics applications, antennas and energy storage facilities. Copper with a conductivity of $\sim 5.96 \times 10^7$ S m^{-1} and silver with a conductivity of $\sim 6, 30 \times 10^7$ S m^{-1} are frequently used in electrical wiring antennas and highly conductive parts. Aluminum (Al 6061) has a relatively low conductivity ($\sim 3.77 \times 10^7$ S m^{-1}), which is often used in satellite structures. Gold ($\sim 4.1 \times 10^7$ S m^{-1}) is used as connectors or coatings because it is anti-corrosive. Titanium alloys are ($\sim 6.0 \times 10^5$ S m^{-1}) used in structural parts where lower conductivity is desired. Carbon fiber composites with conductivities varying from $\sim 10^3$ to 10^4 S m^{-1} are used in antennas and structural reinforcement and are replaced by beryllium ($\sim 2.5 \times 10^7$ S m^{-1}) in satellites. Conductivity and flexibility thus make its application in advanced electronics in space possible and operational. Graphene's extraordinary electrical conductivity, combined with its lightweight and flexible nature, makes it an ideal material for high-performance electronics, sensors, antennas, and energy storage systems in space applications. Its conductivity significantly surpasses those of traditional materials such as copper and aluminium, especially when weight considerations are critical for mission efficiency and launch costs.

3.4. Barrier properties

Gas and liquid impermeability are some of the less known but no less vital attributes of graphene, an ideal material. One layer of graphene is such that nobody – not even the smallest atom such as helium – can pass through it. These features have profound implications for the space applications of this barrier property. It can in some way be used on space vehicles to protect sensitive surfaces on these crafts from various conditions in space, such as radiation, solar winds and micrometeoroids. The fully shielded and oxygen less environment of a spacecraft is another factor that makes graphene fit for creating impermeable and long-lasting closures for spacecraft. Graphene is a single layer covalent mesh made of sp^2-hybridized carbon atoms in a hexagonal array and does not allow the passage of

Table 3 Comparison of the thermal conductivity of graphene with that of other space grade materials

Material	Thermal conductivity (W m^{-1} K^{-1})	Application in space	Ref.
Grap	3000–5000	Heat spreaders, thermal management in electronics and solar panels	31
Copper	390–400	Electrical wiring, heat exchangers	32
Aluminum (Al 6061)	167–218	Structural components, heat sinks, satellite body	33
Silver	420–430	High-efficiency thermal conductors in heat sinks	34
Titanium alloy (Ti-6Al-4V)	6.7–7.0	Lightweight structural components, thermal insulators	35
Carbon fiber composites	10–200	Heat shields, structural materials with limited thermal conductivity	36
Beryllium	200–250	Aerospace structures, lightweight thermal conductors	37
Silicon carbide (SiC)	120–270	Mirrors, heat shields, high-temperature applications	38

Table 4 Comparison of the electrical conductivity of graphene with that of other space grade materials

Material	Electrical conductivity (S m^{-1})	Application in space	Ref.
Graphene	$\sim 1 \times 10^8$	High-speed electronics, antennas, energy storage systems	39
Copper	$\sim 5.96 \times 10^7$	Electrical wiring, antennas, power systems	40
Silver	$\sim 6.30 \times 10^7$	Highly conductive components, wiring, connectors	41
Aluminum (Al 6061)	$\sim 3.77 \times 10^7$	Satellite body, electrical wiring, lightweight structures	42
Gold	$\sim 4.1 \times 10^7$	Electrical connectors, highly resistant coatings	43
Titanium alloy (Ti-6Al-4V)	$\sim 6.0 \times 10^5$	Structural components, low-conductivity parts for the spacecraft	44
Carbon fiber composites	$\sim 10^3$ to 10^4	Antennas, structural materials with low to moderate conductivity	45

gasses even as low an atomic mass as hydrogen or helium. This is because its π-orbitals have an electron density that, under normal pressure, forms a high density of repelling space, which prevents any molecule from passing regardless of the pressure differential. The geometry of the nanopores in graphene is nearly 0.064 nm, which is larger than the size of hydrogen or helium molecules; thus, graphene is impenetrable to all molecular permeation. This impermeability gives rise to several uses, particularly in protective shields, separation membranes in gaseous media, and shielding of fluid samples in electron microscopes. The nonporous property of graphene has applicability in areas such as water protection, an anti-corrosive layer and a selective barrier to diffusion. For example, owing to its inability to let any liquid or gas pass through, graphene can effectively act as a protective shield that is very thin yet very sturdy, helping to protect delicate substances from environmental factors or chemical erosion. From the perspective of the mechanical and chemical properties of the material, it has great production potential in space and other fields of high technology.[46]

The experimental findings presented in Fig. 2 verify monolayer graphene's capability to function as a strong gas-blocking barrier. The measurement data collected by an atomic force microscope demonstrates minimal deflection changes for over thirty days with graphene-sealed microcontainers facing helium gas exposure. Helium represents the most penetrable gas substance because of its small atomic scale. The derived permeation rates for different microcontainer diameters exhibit identical helium permeation rate data points, which remain below the experimental detection thresholds, thus proving that defective-free graphene effectively stops helium gas flow. The experimental setup demonstrated high sensitivity because it successfully detected small deflection measurements under 0.5 nanometers. The research results demonstrate graphene's value in extreme gas containment systems such as spacecraft applications. Defect-free uniform sealed membranes are essential for

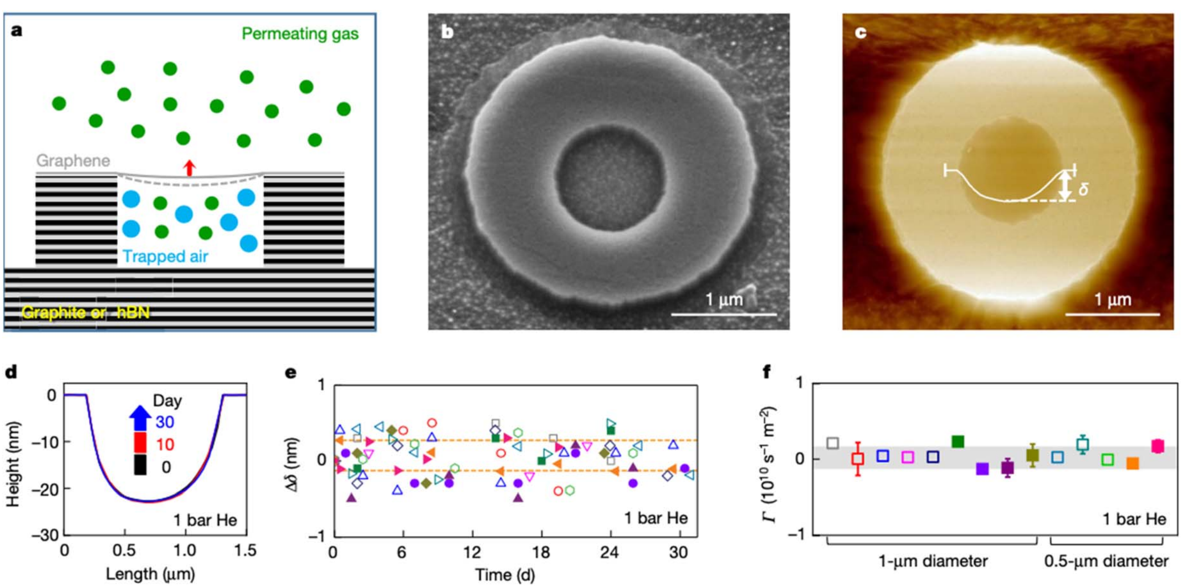

Fig. 2 (a) Monolayer graphene's capability to block gases through a graphene membrane covering microcontainer air storage, which undergoes gas permeation while trapped under a sealed condition. (b) A sealed microcontainer revealing its graphene membrane features using electron micrograph imaging. (c) Atomic force microscopy (AFM) image showing deflected graphene membrane surfaces. (d) AFM profiles showing the time-evolved behavior of suspended graphene membranes functioning without noticeable deflection while exposed to helium at 1 bar pressure over 30 days. (e) Statistical variations in membrane deflection. (f) Deflection-based gas permeability measurements established the insulating nature of various microcontainers with diameters ranging from 1 µm to 0.5 µm against helium penetration.[47]

graphene impermeability because they prevent gas leakage in demanding conditions consisting of elevated pressures or prolonged durations of exposure.

Space applications depend on lightweight gas impermeability, and these findings present potential difficulties along with promising prospects. The ultrathin and lightweight structure along with the theoretical impermeability of graphene qualify the material as an efficient barrier choice for protecting spacecraft systems. The material remains vulnerable to hydrogen permeation, especially in environments with high hydrogen levels. The performance of graphene increases when manufacturing techniques advance to minimize fabrication defects and achieve a stable ripple configuration. The development of these techniques has become essential because space technologies require dependable gas retention systems and material stability under space conditions.[47]

Similarly, aluminum oxide (Al_2O_3) is used in protectors or protective coatings owing to its high degree of resistance to corrosion and for the encapsulation of electronics.[48] Polyimide (Kapton), although gas and liquid resistant, is a common feature in space applications used in thermal insulation, space blankets, and protective films because it is UV radiation and temperature resistant.[49] Silicon dioxide (SiO_2) has very low permeability of gases, very high thermal stability, and reasonable chemical resistance; therefore,[50] for barrier coatings on electronics and spacecraft windows, it is the most suitable. Gold, which cannot be penetrated by gases, oxidized, or corroded, is employed to metallize electronic parts, contact points, and optical parts in spacecraft.[51] However, aluminum (Al 6061), which also finds usage in spacecraft structural parts, has relatively moderate permeability to gases and needs to be surface-treated to protect against oxidation and corrosion.[52] Another material with high gas impermeability, corrosion resistance, and UV resistance is titanium dioxide (TiO_2), which finds application in solar cells and as a protective coating layer in spacecraft.[53] For example, Teflon (or polytetrafluoroethylene, PTFE), which is chemically inert and hydrophobic and has a reasonable gas permeability rating of 54,[54] is used in spacecraft coatings, thermal insulation, seals, and gaskets. Finally, Beryllium Oxide (BeO), owing to its high corrosion resistance and low permeability to gases, is used as a thermal coat and as a protective layer for high temperature launching applications.[55] These latter materials combined give rise to several solutions to such extreme climatic conditions of space. Graphene is highly hydrophobic, as well as chemically inert and immune to corrosion; thus, it is an ideal material for use in space barriers. It provides a more enhanced shield to spacecraft surfaces and sensitive electronics than aluminum oxide, silicon dioxide and gold. This makes graphene a perfect candidate for a form of space varnish or a membranous sheath that helps shield spacecraft hardware from the pressures of space and increases the useful lifetimes of most afflictive space parts.

3.5 Radiation shielding

Space experiments also underline the need for materials resistant to high-energy cosmic radiation and solar particle events that are inevitable in space missions. Graphene has been considered for radiation shielding applications because of its high electron density and mechanical properties. A nuclear structure of graphene is bent or can react to high energy particles so that it can shield both spacecraft and astronauts from radiation. This property may be critical for long-term space exploration, including manned Mars missions where radiation risk is known. Fig. 3 shows that graphene possesses a very good radiation shielding capability, which shows that it is suitable for spacecraft radiation shielding and the protection of sensitive electronic components in satellite operations. This efficiency is due to the strong electric charge density, which makes its shield efficiently guard against cosmic radiation and solar winds.[56]

Aluminum (Al 6061), although extensively employed in spacecraft structure and housing in the structure and body of the spacecraft, provides decent shielding but is not efficient against heavy core rays.[57] Polyethylene (PE) offers high shielding efficiency, especially for galactic cosmic rays (GCR) and solar particle events (SPE) and thus is recommended for radiation shielding within human space habitats and spacecraft.[58] Another compound is Boron Nitride Nanotubes (BNNTs), which are claimed to have high shielding efficiency because of their

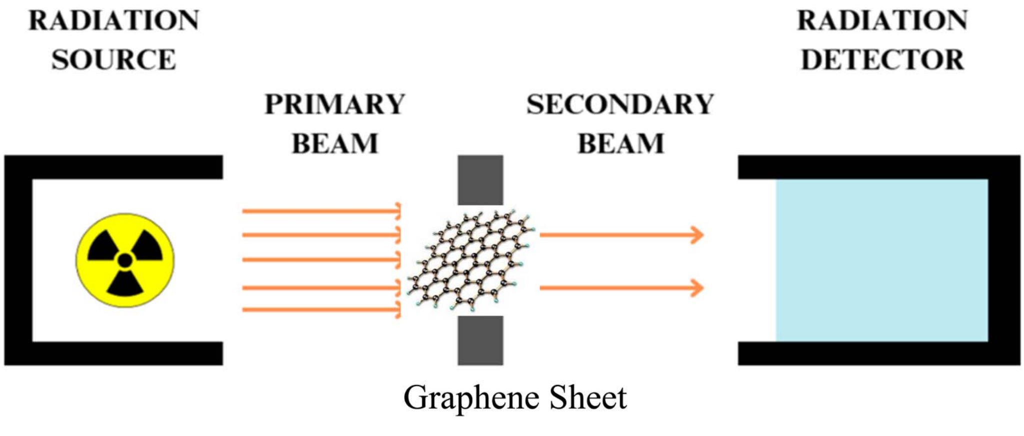

Fig. 3 Demonstration of radiation protection through a graphene shield.

characteristics in neutron absorption and gamma radiation exclusion. They are being researched for applications in shields for spacecraft radiation and the guarding of electronics.[59] Lead (Pb) has good gamma radiation-attenuation characteristics but has high density, making it unsuitable for space use although it is used in nuclear power plants.[60] Kevlar, an aramid fiber, is moderately effective for radiation shielding besides offering protection against micrometeoroids and therefore can be useful in spacecraft structures and astronaut garments.[61] Titanium Alloy (Ti-6Al-4V) has some good characteristics, for example, moderate shielding efficiency but lightweight, used for spacecraft structures because it is basically resistant to solar radiation.[62] Finally, water, although heavy, has high efficiency for protection against SPE and GCR and is widely used in human living spaces for protection against radiation.[63]

Graphene has been identified as one of the best shielding materials for radiation in space owing to its light-weight nature, high electron density and strength. It can surpass some standard materials, such as aluminum; the material allows for collaboration with polyethylene in shielding spacecraft and astronauts from GCRs and SPEs. Furthermore, graphene can be incorporated into structural materials, such as aluminum or titanium, for improved radiation shielding and structural reinforcement. Subsequent designs of spacecraft will probably employ graphene to guarantee enhanced sturdiness and shield against space conditions.

3.6 Flexibility and transparency

Apart from its elasticity, graphene is also remarkably tough because it can bend along with stretch without rupturing; hence, it is useful for flexible electronics and foldable solar sails in space stations. Further, graphene exhibits transparency in the visible region of the spectrum; the graphene sample absorbs only 2.3% of visible light. This transparency in addition to its high conductivity makes it suitable for transparent conducting coatings on solar cells, increasing their efficiency without adding bulk. Graphene is highly flexible – it can be bent and stretched – and is >97.7% transparent to visible light. These properties make it largely suitable for use in bendy electronics, optically clear thin films and other electrical devices, such as space solar panels.[64] The high optical and electrical performance shown in Fig. 4 makes graphene an ideal material for future space applications. The optical transmittance data presented in panel Fig. 4a confirms the theory by showing that

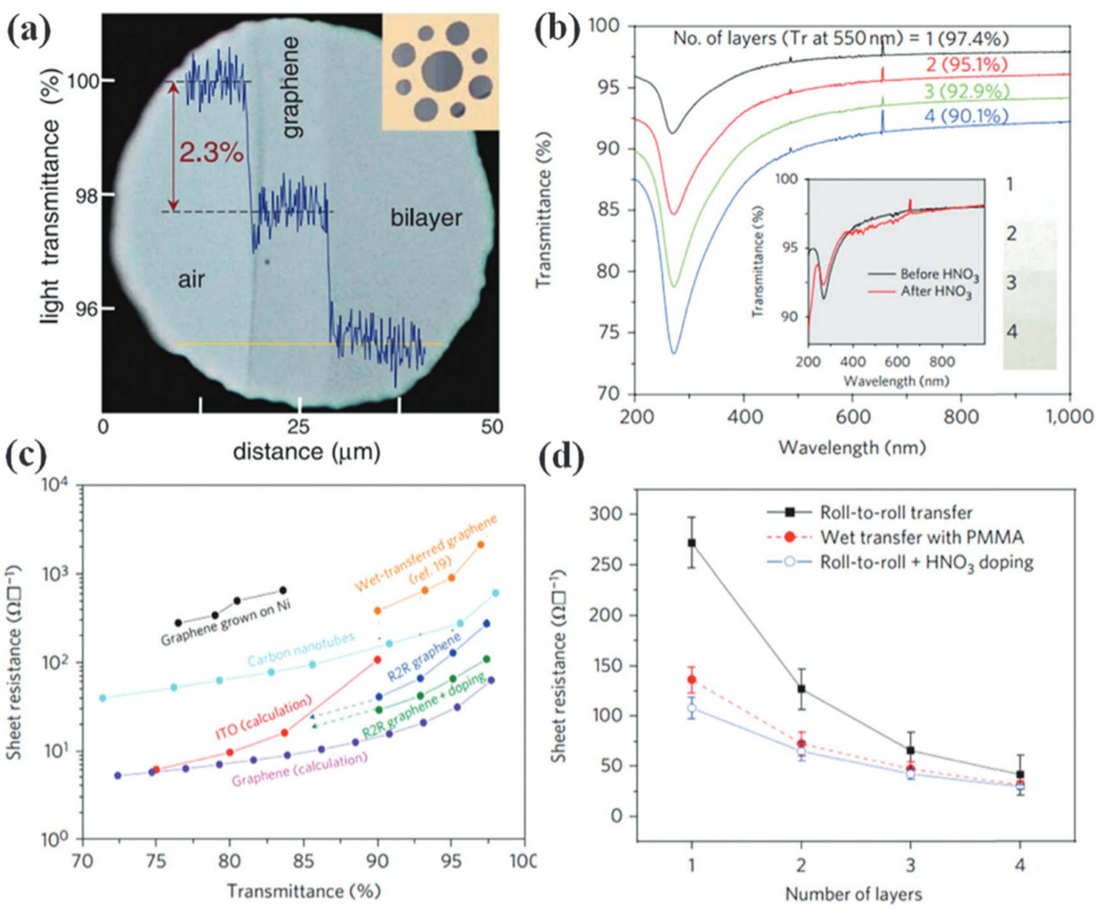

Fig. 4 (a) Monolayer graphene demonstrating an optical transmission of 2.3% light absorption transitioning into bilayer graphene with improved performance. (b) Doping of the layers with HNO_3 improves the decreased transmittance effect observed with increasing layers. (c) A comparison of sheet resistance against transmittance revealing that graphene surpasses both ITO and CNTs as a superior material. (d) Roll-to-roll transfer technology combined with HNO_3 doping enables performance enhancement for advanced applications while demonstrating scalability.[67]

monolayer graphene absorbs 2.3% of light. The exceptional transparency and flexible customization of bilayer graphene demonstrate its suitability for generating space-critical transparent materials used in solar arrays and optical systems. Single-layer graphene preserves 97.4% of light transmission, while multiple graphene layers reduce optical transparency according to panel (b) data at 550 nm. Water solutions of HNO_3 improve graphene material specifications for space applications, where transparent conductor optimization is essential. The results in panel (c) show that chemically doped graphene stands out by offering higher transmittance rates and lower sheet resistance than both carbon nanotubes and ITO among other materials. Portability combined with efficiency defines graphene as an optimal material for space applications involving solar power generation and energy collection. The assessment of sheet resistance *via* panel (d) demonstrates that sheet resistance declines, while scalability rises when utilizing roll-to-roll transfer accompanied by HNO_3 doping. The ability to scale graphene makes it an essential component for developing large-area flexible electronics alongside serving as a radiation shielding material while powering durable spacecraft components. Space technology development benefits significantly from graphene's exceptional transparency capabilities at low resistance value together with its versatile nature.[67]

However, indium tin oxide (ITO) is normally more brittle and can easily crack under stress, with a transmission rate constitution of eighty five percent to ninety percent most commonly applied in the fabrication of infrastructural transparent conductive coatings for space electronics and photovoltaic applications.[65] Polyimide (Kapton) is not stretchable but flexible, and it is also not translucent and therefore better suited for thermal shielding than for space blankets.[66] A particularly useful elastomer is polydimethylsiloxane (PDMS), which has the advantage of being highly flexible and stretchable: it has a transmittance rate of between 92% and 95% with respect to visible light, and it could therefore be used for flexible and simultaneously clear coatings or as an encapsulant layer for electronics.[67] Hexagonal boron nitride (h-BN) is flexible like graphene but slightly more inelastic and transparent just in the UV range, so it serves well as a barrier in UV-related applications and heatsinks.[68]

Polyethylene terephthalate (PET) usually employed as a substrate for flexible electronics is flexible and 90% transparent in the visible light range and thus is used in flexible display and solar modules and in radiation shield films.[69] Silver nanowires (AgNWs) have moderate flexibility with poor fracture toughness that cracks severely under stress, and its transparency is in the range of 85–90% and is used in transparent conductive layers, flexible circuits, and electronics.[70] Finally, ITO/AgNW composites have mechanical flexibility over ITO alone, with transparency varying in the range of 88–92% and are suitable for flexible display and transparent conductive films.[71] Given its flexibility and high transparency, it has the potential to be used in advanced space solutions, such as wearable electronics, flexible photovoltaics and transparent conductor layers. It presents higher resistances of strain, is optically transparent to a greater extent than ITO or silver nanowires, and shows much more mechanical resistance to the stresses typical of space conditions. Additionally, for adequate use in solar energy collection or with all optical applications in space, the graphene barrier has high transparency.

3.7. Chemical stability and corrosion resistance

Graphene exhibits low chemical reactivity and hence has high resistance to corrosion, which is an important factor in space applications as materials exposed to harsh conditions are quickly eroded. Surface-coating spacecraft parts with graphene can preserve the survival of important structures by resisting phenomena such as oxidation, corrosion, and chemical reactions in space or in the terrestrial atmospheres of planets.

Graphene excels in chemical inactivity and corrosion protection ability, which makes it suitable for application on the exterior shield of spacecraft and electronic devices because it is gas and liquid proof. Fig. 5 illustrates that graphene exhibits excellent ability as a protective layer against oxidation attacks for copper and copper–nickel alloys. This repealing layer is composed of a thin layer of graphene by chemical vapor deposition and does not allow access to oxygen or other reactive agents in the metal. Helium (He) also mentioned that such an ability stems from the fact that graphene cannot dissolve in any solvent, and it is chemically and thermally stable because it does not burn even at high temperatures. Fig. 5a and b depict two sets of samples, namely the graphene-coated copper coins and the copper–nickel alloy foils, treated with hydrogen peroxide. The samples without the graphene coating were greatly discolored and damaged compared to the samples protected by the graphene layer, and the results indicated that graphene can act as a chemical barrier. Fig. 5b and c illustrate the coated samples with graphene heated at 200 °C for some hours. The copper and copper–nickel alloy experimental samples had the least oxidation and turned black after some time similar to the uncoated samples owing to oxidation. Graphene-coated samples remained unaffected, meaning that they offered better protection. This study supports the vast usage of graphene as a corrosion inhibitive, thin film coating that does not significantly alter the mass or thickness of metal systems, an area of profound importance in high demand industries where robust, lightweight materials are desirable.[72]

Aluminum (Al 6061) has only mediocre chemical resistance; it dissolves in certain acids and alkalis and is not suited for space use in its pure state, and it needs anodizing or a coating for this purpose.[73] It is widely employed in the construction of structural members and in the structures of spacecraft.[74] The type of titanium alloy that Chew's Airline uses is Ti-6Al-4V; it has high chemical stability with excellent corrosion resistance and is best suited in space and marine application, structural parts and radiation shielding.[9] 316L is a highly stable austenitic stainless steel with excellent oxidation and chemical resistance, with the necessary corrosion trained for use in fasteners and other structural components.[75] Gold is chemically inactive and does not oxidize, so it does not corrode in space; it is useful for protective layers and conducting parts for electronics.[76] A practiced engineering material is polyimide (Kapton),

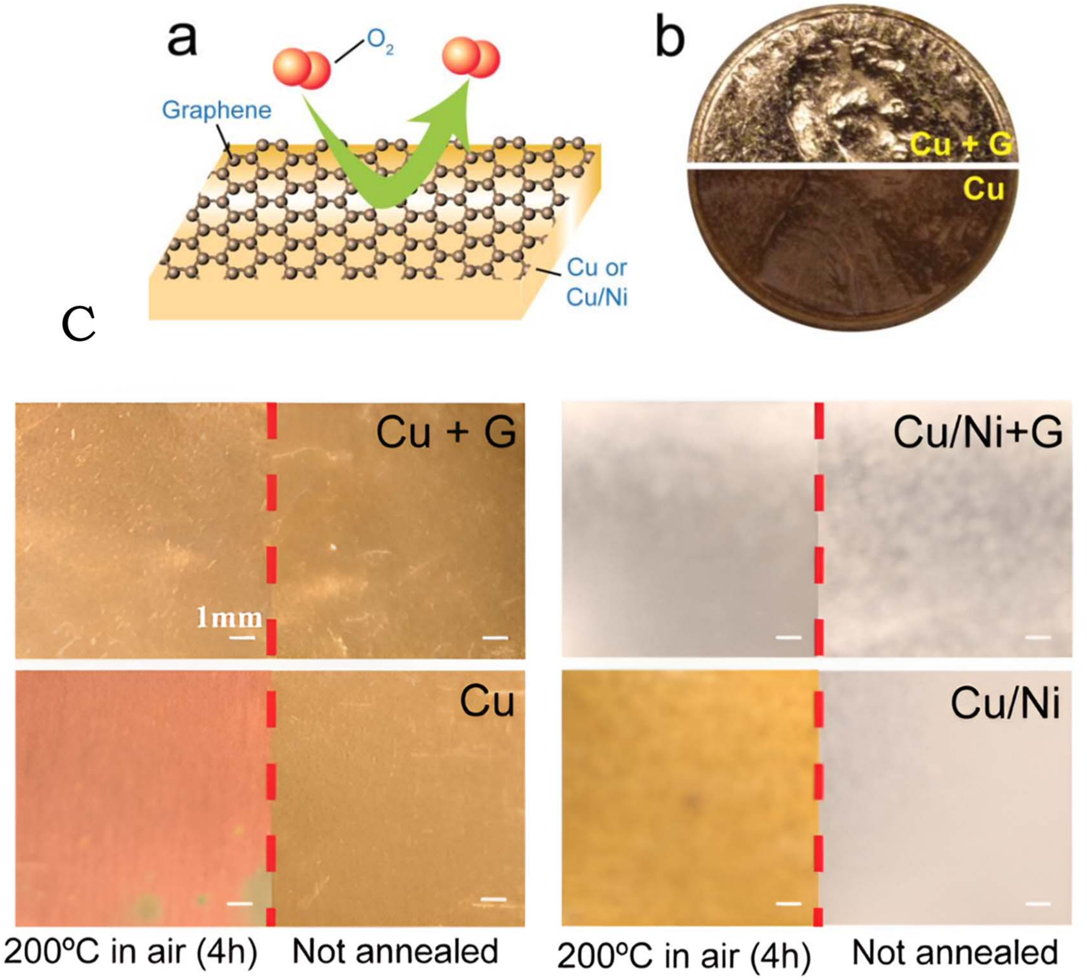

Fig. 5 Specific case of using graphene as a corrosion prevention layer described based on tests with copper and copper–nickel alloy. As described in (a) and (b), the present results reveal that graphene-protected Cu and alloy foils exhibit much lower oxidation compared with uncoated samples when exposed to H_2O_2. In (c) the measured reflectance values show that graphene-coated metals do not oxidize when heated up to 200 °C in air and retain their metallic shine unlike the uncoated samples that oxidize and turn black.[72]

specifically for spacecraft insulation and thermal protection, because it has high chemical stability and good corrosion resistance although it can degrade under long term UV exposure.[77] BNNTs show high chemical stability and good corrosion resistance, especially for radiation and oxidation,[78] and thus can be used as structural elements or radiation protectors. Teflon (PTFE) is chemically very stable, does not corrode at high temperatures and is suitable for use in spacecraft as a seal, gasket, and thermal barrier.[79] Conversely, magnesium alloy (AZ31) has low chemical stability and poor corrosion resistance, especially in areas of high humidity for which the material requires coatings so that it can be used in lightweight spacecraft parts.[80]

3.8. Lightweight nature

It is enhanced with a high degree of properties; nevertheless, the weight of graphene is microscopic. The density of one layer of graphene is 0.77 milligrams per square meter. This extremely low density has the advantage of making graphene highly suitable for use in space vehicles and satellites, where every kilogram of material saved in the structure can accommodate a scientific instrument or fuel. Another reason graphene is being widely researched with regard to its application in aerospace vehicles is its valuable quality, which allows for the overall mass of space vehicles to be significantly decreased while retaining structural integrity and performance. Unifying desirable features, such as a low density of about 0.0023 g cm^{-3}, graphene is suitable for space vehicle structural parts, sensors and thermal control systems.[81] However, the aluminum (Al 6061) mixture comes in 2.70 g cm^{-3} and can be commonly observed in spacecraft and satellites, as well as in the manufacturing of aerospace products owing to the material's high strength-to-weight ratio.[82] Carbon fiber composites, with densities in the range of 1.75–1.95 g cm^{-3}, are widely used in spacecraft structures and satellite parts owing to their high strength and low weight.[83] Titanium alloy (Ti-6Al-4V) however has a density of 4.43 g cm^{-3} and is applied in structural aerospace parts alongside shielding against radiation.[84] Magnesium alloy (AZ31) with a density of 1.78 g cm^{-3} is preferred in light weight spacecraft structures.[85] Ceramic composites, including Boron Nitride Nanotubes (BNNTs) with a relative density of 2.1–2.3 g cm^{-3}, are high strength lightweight composites used in radiation shielding.[86] Polyethylene (PE) has a density of 0.94 g cm^{-3} and is used in radiation shielding in addition to in structural applications.[87] Kevlar with a density of 1.44 g cm^{-3} is used to offer protection against micrometeoroids.[88] Aluminum oxide (Al_2O_3) is applied as protective coatings and spacecraft windows and has a density of 3.95 g cm^{-3}.[89] Silicon dioxide (SiO_2) is used in spacecraft coatings, insulation, and spacecraft windows, and it possesses 32.65 g cm^{-3} density.[90]

Thus, aside from its boasting remarkable features, graphene is and remains almost incredibly light. One graphene layer in terms of areal density is approximately 0.77 mg m^{-2}.[91] This ultra-low density when linked to other unique properties makes it suitable in applications that require high strength/weight ratios, such as in spacecraft or satellites, where every kilogram of structural weight saved can mean the carrying capacity of more instruments or fuel. Another advantage, which is possibly even as attractive as that of hardly increased density, is the fact that graphene can enable the lightening of load-carrying space frames with the simultaneous preservation of their strength and performance characteristics. This inclusion illustrated how graphene's extremely low density qualifies it to be a highly effective material when it comes to the space industry, where weight cut on any structural material is critical. Unlike conventionally employed materials, such as aluminum, carbon fiber, and titanium alloys, graphene provides a substantially lower density and equal or better mechanical properties and performance. Graphene composites and coated structures, spacecraft materials, electronics, and thermal radiators can be made lighter by leveraging graphene reinforcement, thus making space missions cheaper and more efficient.

3.9 Spacecraft energy storage

Comparing graphene to other battery materials in the context of its application for spacecraft, two key points can be stated: first, the use of graphene increases the density of energy in the spacecraft; second, its use reduces its weight and improves the power output. The above-mentioned energy density of graphene is up to 1000 W h kg^{-1},[92] which is much higher than those of lithium-ion batteries (250 W h kg^{-1}) and nickel–cadmium batteries (150 W h kg^{-1}) (Table 5).[93,94] This means that more energy can be packed into a kilogram of graphene-based batteries, which is very vital in space exploration where weight is a major issue and energy is required in large proportions for long-duration space missions. In terms of weight, the position of graphene is considered very light weight, lithium-ion batteries are moderately light in weight, and nickel–cadmium batteries are heavy. This makes graphene the perfect choice for spacecraft because the product used needs to be very light to reduce the costs of launch and increase fuel utilization. Additionally, graphene provides a high power density and thus would be useful in applications requiring high power, such as applications in spacecraft propulsion and power-intensive appliances. Similarly, nickel–cadmium batteries give low power density, while lithium-ion batteries offer a comparatively moderate density. The cycle life is also higher, with graphene holding a capacity of over 10 000, while lithium-ion can handle only 500–1000 charge cycles and nickel–cadmium can handle 500–800 cycles. This makes graphene a highly durable and cheaper solution because longer lasting batteries do not require frequent replacement and frequent servicing during long space expeditions.[95–97] Graphene also exhibits great stability when subjected to higher temperatures, which is another important factor in space. Although both graphene and solid-state batteries are highly resistant to high and low temperatures, nickel–cadmium batteries have moderate resistance. Finally, radiation resistance is another important factor in space applications, where graphene has superiority over other materials in this context because it has a higher Rrs to space radiation (Fig. 6). This ability to protect against cosmic rays and solar radiation guarantees the efficiency of graphene-based batteries to support both spacecraft electronics and mission goals.[97–99]

Overall, the above-mentioned tree diagram shows different uses of graphene with a special emphasis on its usage in space technology and aerospace fields. The diagram is divided into four primary categories (Thermal management, structural reinforcement, electronics and communication, and radiation protection subsections) to spell out the usefulness of graphene. In thermal management, the ability of graphene to dissipate heat greatly can be employed to regulate and minimize heat generation around spacecraft electronics and sensors for appropriate space conditions. Furthermore, graphene is used in thermal layers, on which form the outer surfaces of spacecraft, to help protect the spacecraft from extreme heat from the sun and extreme cold from space. In the case of structural reinforcement, the new material's advantage is improved strength and low density of graphene. In spacecraft frames, the application of graphene composites also has the added advantage of slightly reducing the total mass of spacecraft, with an equivalent or better strength than conventional materials, which is a key factor in fuel consumption and loading. In the same way, satellite components manufactured using graphene-related

Table 5 Comparison of the energy storage of graphene with that of other space grade materials

Material	Energy density (W h kg^{-1})	Weight	Power output	Lifespan (charge cycles)	Radiation resistance	Ref.
Graphene	1000	Lightweight	High	>10 000	High	92
Li-ion	250	Moderate	Moderate	500–1000	Moderate	93
Ni–cad	150	Heavy	Low	500–800	Low	94

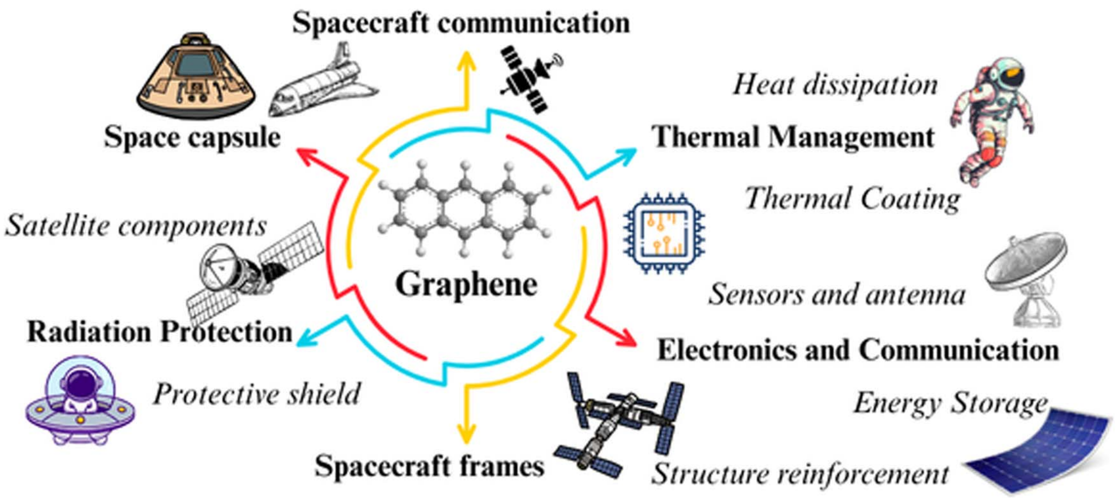

Fig. 6 Summary of the tree diagram of various applications of graphene for spacecraft applications.

materials are lighter and sturdier than metal components, increasing the operational satellite lifetime in space. In electronics and communication, the electrical characteristics of graphene suggest a high potential for the next generation of sensors and antennas. These graphene-based parts enhance the accuracy, rate and reliability of the signal interconnect between satellites and the ground station, which in turn boost the communication systems. Additionally, the application of graphene in energy storage in the form of both supercapacitors and batteries gives a lightweight, high-capacity power supply for long duration space missions. Finally, radiation protection is probably one of the most valuable uses of graphene within the context of space. The ability of graphene to safeguard vulnerable electronic equipment and astronauts besides shielding or capturing injurious cosmic rays and ultra-violet solar radiation should equally merit significant attention. Thus, it illustratively demonstrates how graphene, being lightweight, strong, thermally, electrically, and radiation conductive, is the material of the future space and advanced aerospace technologies. The following table shows how graphene compares to typical aerospace metals and composite materials, including aluminum alloys, titanium alloys, and carbon fiber compounds. Our comparison uses basic performance indicators, including strength-weight ratio, heat transmission rate, manufacturing expenses, and joining ability (Table 6).

4. Summary and outlook

4.1. Summary

We investigate the advantages of using graphene technology to enhance aerospace systems designed for space travel and exploration. The outstanding physical abilities of graphene's single-carbon sheet make it an excellent solution for fixing the technical issues that affect spacecraft and satellite performance. As a space technology innovator, graphene exhibits remarkable

Table 6 Comparison of graphene to typical aerospace materials, including aluminum alloys, titanium alloys, and carbon fiber composites, through major performance evaluations such, as tensile strength, density, strength-to-weight ratio, thermal conductivity, electrical conductivity, engineering costs, integration simplicity, and durability under space conditions[100,101]

Property	Graphene	Aluminum alloys (*e.g.*, 6061-T6)	Titanium alloys (*e.g.*, Ti-6A-4V)	Carbon fiber composites
Tensile strength (GPa)	130+	0.3–0.4	0.9–1.1	3.5–6.0
Density (g cm^{-3})	0.0023	2.70	4.43	1.75–1.95
Strength-to-weight ratio	Extremely high	Moderate	High	Very high
Thermal conductivity (W m^{-1} K^{-1})	3000–5000	167–218	6.7–7.0	10–200
Electrical conductivity	Excellent ($\sim 1 \times 10^8$ S m^{-1})	Good ($\sim 3.77 \times 10^7$ S m^{-1})	Moderate ($\sim 6 \times 10^5$ S m^{-1})	Moderate
Cost	High (due to production limitations)	Low	High (but cheaper than graphene)	High
Ease of integration	Challenging (due to processing issues)	Easy (widely used in aerospace)	Moderate (requires specialized processes)	Moderate (requires precise fabrication)
Durability in space conditions	Potentially excellent but needs further testing	Good (corrosion-resistant)	Excellent (high strength and durability)	Good (but susceptible to UV degradation)

performance owing to its strong bond strength and superior thermal and electrical capabilities. The material's low density helps cut down spacecraft weight while making flights longer and carrying heavier loads. The work reveals graphene's ability to boost aerospace performance by reinforcing components, managing heat, blocking radiation and storing energy. Researchers have shown that graphene composite structures effectively boost spacecraft protection with reduced weight, resulting in superior space operation. The excellence of its radiation protection feature ensures that astronauts stay safe while helping shield delicate electronics from space radiation. The energy storage capabilities of graphene allow long-space missions to function better by delivering more power with less equipment mass.

4.2. Outlook

Graphene shows great promise for aerospace use, but its implementation in aerospace remains under development. Goals still stand to make graphene production at scale while reducing production costs for space mission composites. The aerospace industry needs advanced graphene production research based on chemical vapor deposition and liquid-phase exfoliation to lower costs and improve accessibility. To advance graphene in space applications, we must work through current challenges while performing tests in real-world settings. Future studies will examine how to better connect graphene to aerospace materials to build composite materials in which graphene works together with aluminum, titanium and carbon fiber for optimal results. We need to study how UV light and radiation affect graphene stability, so we can keep this material effective through extended missions in space. Spacecraft and satellite developers will benefit from using graphene to build more technology that saves energy and stays strong. Graphene's adaptable nature may support innovative developments in space habitats and deep space protection systems as well as flexible transparent electronic solutions for upcoming space missions. The future development of graphene technologies will transform aerospace operations through improved spacecraft designs that deliver efficient and sustainable space exploration.

Data availability

All necessary data are shown in the figures and tables within the document.

Author contributions

Praveen Kumar Kanti: conceptualization, methodology, investigation, and writing; Prashantha Kumar H G: writing & editing and supervision; V. Vicki Wanatasanappan: methodology, investigation, editing, and writing; Abhinav Kumar: writing & editing; and Melkamu Biyana Regasa: conceptualization, methodology, and writing & editing.

Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

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