

Synthesis and Promising Applications of Graphene and Related Materials

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Abstract: In recent years, there has been extensive research on graphene and its derivatives, driven by their remarkable physicochemical and functional properties. Various forms of graphene, such as multi-layer graphene, graphene oxide, and graphene quantum dots, have shown immense potential to revolutionize multiple technologies. This review critically examines the synthesis and applications of graphene and related materials. In the synthesis section, we explore methods ranging from top-down techniques, which involve breaking down larger structures into graphene layers, to bottom-up approaches, where graphene is built up from smaller constituents. In the application segment, we comprehensively discuss the diverse uses of graphene and its derivatives. This includes their roles in electronic applications, energy storage systems, tribological applications, healthcare technologies, water desalination processes, and mechanical applications. By exploring various applications, we aim to highlight the wide-spread applications of graphene-based materials and their composites in shaping the future of multiple technologies.

Keywords: Graphene, Electronics, Energy storage, Tribology, Healthcare

1. Introduction: Graphene, a promising multifunctional material, has vast applications from pencil lead[1] to neural computing [2]. Graphene can be rolled, bundled, and stacked into 0D (fullerene, graphene quantum dots) [3, 4], 1D (nanotube, nanoribbon), and 3D (graphite) materials. The chemical model of graphene is depicted in Figure 1. Graphene exhibits exceptional properties such as high electron mobility which is 200 times higher than that of silicon under ambient conditions, ballistic electrical conductivity of $\sim 10^3$ S/m, thermal conductivity of ~ 5300 W/mK, excellent mechanical properties like ultimate tensile strength (UTS) of 130 GPa and elastic modulus of ~ 1 TPa, very high specific surface area of 2630 m²/g, excellent optical transparency ($\sim 97.7\%$), and less break-over voltage of ~ 0.3 V [5-11].

Due to these astonishing properties graphene and graphene-related materials (GRMs) are extensively used in different applications. Researchers have used various methods to synthesize graphene to obtain desirable

properties and potential applications. To expand their usage, the chemical modifications of GRMs have also been executed. Despite the fact that graphene will probably enter the market as a composite, several teams are attempting to realize the full potential of the isolated sheets.

In this review, we critically discuss the synthesis and properties of graphene and GRMs. We compiled recent literature on graphene and GRMs and discussed their potential applications in the fields of high strength systems, electronics, healthcare, sensors, tribology, water desalination, and composites.

2. Synthesis of graphene: The synthesis of single-layer graphene was tried in 1975. The researchers showed that single and multilayer graphene could be produced by thermal decomposition of carbon on Pt crystal as a substrate.

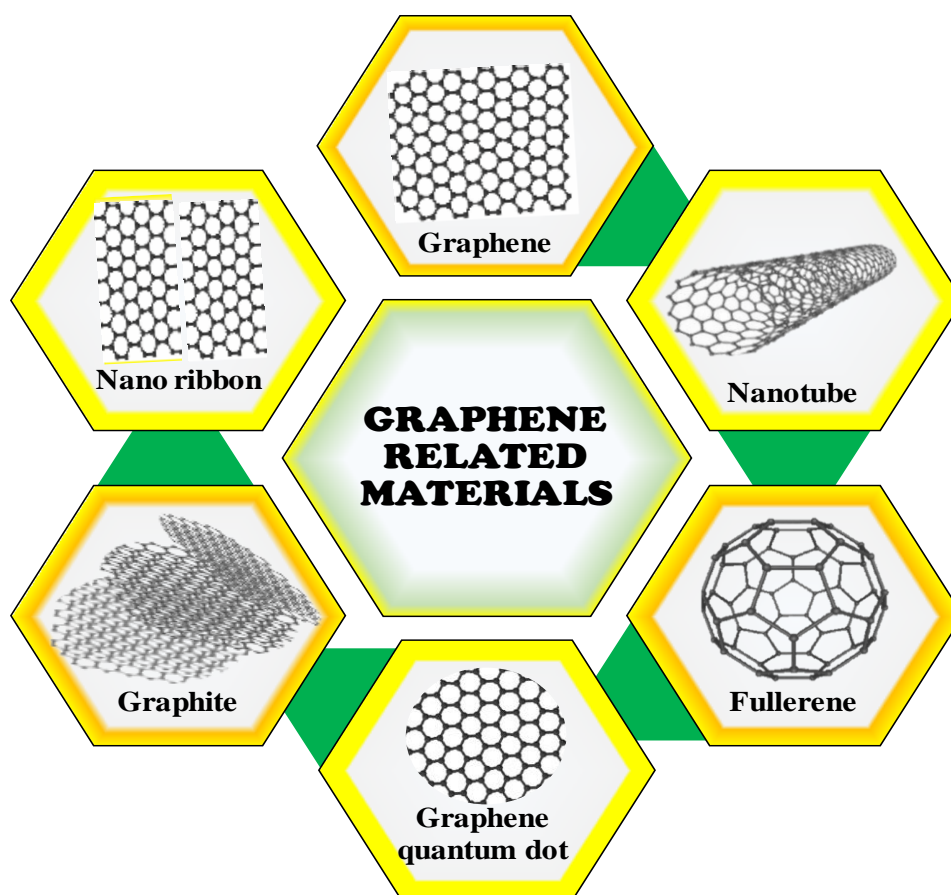


Figure 1. Chemical model of graphene-related material.

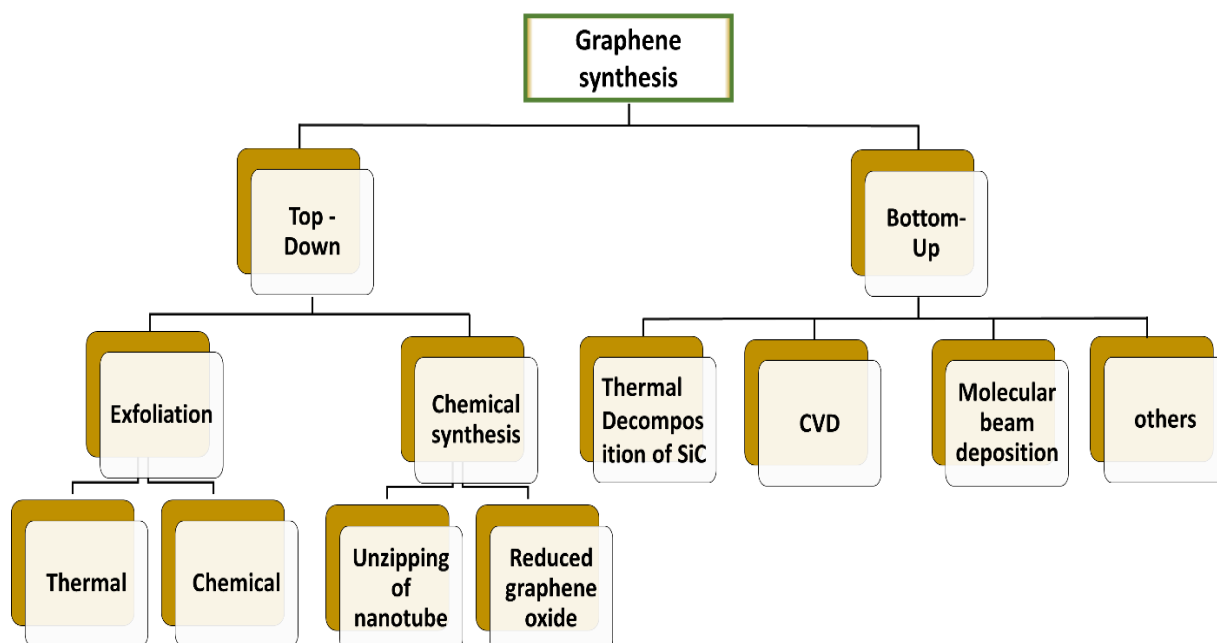


Figure 2: Graphene synthesis method

However, due to the lack of understanding about such sheets and the failure to find the potential applications of these sheets, a

detailed study was not conducted at that time. Later on, in 1999, scattered efforts were reported for the synthesis of graphene.

However, in 2004, Geim and Novoselov were credited for the discovery of graphene [12]. For the first time, they showed the repeatable synthesis of graphene through exfoliation. After that, several methods have been reported and some of the most important synthesis (Figure 2) methods are discussed below.

2.1 Exfoliation: In graphite, the graphene sheets are bonded together by weak van der Waals bonds. These bonds can be broken to produce graphene from graphite. In exfoliation processes, mechanical or chemical energy is used to break these weak bonds and separate individual graphene sheets.

2.1.1 Chemical exfoliation: This method uses a liquid suspension that converts graphite to graphene through the formation of an intermediate compound known as a graphene-intercalated compound. Alkali metals are used to increase the interlayer spacing between the graphite layer by reducing the van der Waals forces, as these large alkali ions are placed in between the graphitic layer of graphite dispersed solution, owing to the potential ionization difference between the graphite and alkali metal. Chemical exfoliation has the benefits of a high yield and low operating temperature, but the graphene it produces tends to reassemble into graphite, hence surfactants or immiscible liquids are required [13].

2.1.2 Mechanical exfoliation: One of the most effective methods for obtaining single-layer graphene flakes on desired substrates is mechanical exfoliation. In this method the peeling of the graphitic layer is happened with the help of scotch tape, ultrasonication, electric field, or even the transfer printing technique. Geim and Novoselov used mechanical exfoliation for the development of graphene [12]. They used highly oriented pyrolytic graphite (HOPG) to create 4-5 μm deep mesas. The flakes of graphene were peeled from mesas using scotch tape. These flakes were washed with acetone several times and put onto the silicon substrate.

2.2 Thermal Chemical Vapor Deposition Techniques

(i) *Thermal Decomposition of SiC*

The graphene can be synthesized using the thermal decomposition of silicon carbide. In this technique, SiC is heat-treated up to temperatures ranging from 1200-1500°C in an ultra-high vacuum. This leads to the removal of Si, thus leaving behind a layer of carbon [14]. Transmission electron microscopy studies were used to confirm the graphitic nature of the carbon layer or graphene. The ultrathin epitaxial films of graphite were grown by this technique on the 6H-SiC surface. The films typically contain mono and bilayer graphene sheets [15]. The primary benefit of the thermal breakdown of SiC over other traditional methods is the direct production of graphene layers on a semiconducting or semi-insulating substrate that is readily accessible for purchase, negating the need for transfer before processing electrical devices.

(ii) *Molecular Beam Deposition*

This technique is successfully used for the graphene growth on a variety of substrates. For example, ethylene gas is used as a carbon source and Ni substrate is exposed to a higher temperature (200°C) in an ethylene gas environment. High-quality graphene layers can be produced by this method and are capable of forming a layer on top of another [16]. The main advantage of this method is that the graphene layers are not dependent on the cooling rate which indicates that carbon was not absorbed into the Cu and Ni substrate as in CVD processes.

(iii) *Chemical Vapor Deposition.*

In the chemical vapor deposition (CVD) technique, one can produce graphene on the transition metal (e.g. Fe, Co, Ni, Cu) at high temperature (>1000°C) with the carbon source supplied in gas form and metals like Cu and Ni is preferred as a substrate to grow the graphene layer [17-19]. Methane and acetylene gas are generally used as a source of carbon. Along with methane, hydrogen and argon are also utilized as reaction stabilizers and to improve the homogeneity of the film [20]. Furthermore, the CVD approach can be

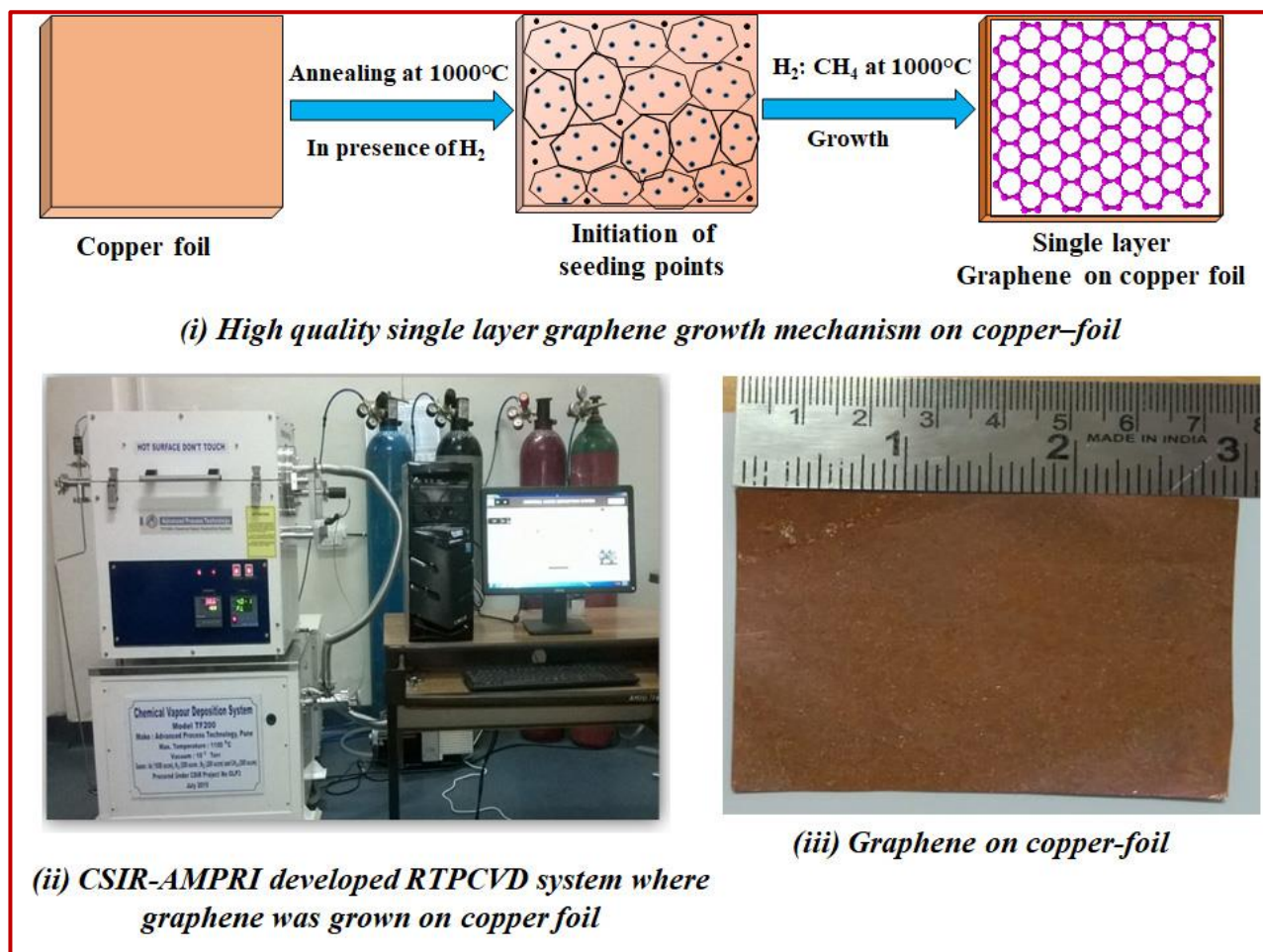


Figure 3. Synthesis of high-quality single-layer graphene and its characterization at CSIR-AMPRI, Bhopal.

modified and enhanced, including atmospheric pressure CVD (AP-CVD), radio-frequency PE-CVD (RFP-CVD), microwave plasma CVD (MP-CVD), ultra-high vacuum CVD (UHV-CVD), plasma-enhanced CVD (PE-CVD), low-pressure CVD (LP-CVD), inductively coupled PE-CVD (ICP-CVD), and surface-wave plasma CVD (SWPCVD). A good quality graphene layer growth was demonstrated using rapid thermal process (RTP) CVD (Figure 2). For graphene deposition, firstly, Cu foils are placed in a quartz tube and heated up to 1000°C in an H₂ atmosphere for 30 min to remove residual oxide. After annealing, the sample is cooled down to room temperature. Following the preconditioning step, the Cu foil is again heated up to 1000°C and subsequently CH₄ and H₂ gases are introduced for 20-30 min leading to growth of graphene. After growth

the sample is cooled down to room temperature.

2.3 Chemical Methods

i) Chemical oxidation and reduction

A large amount of graphene can be produced through the oxidation of graphite by treating it with strong acidic and basic oxidants. It was first introduced by Brodie in 1859 when graphite was treated with potassium chlorate (KClO₄) and fuming nitric (HNO₃) and NO₂. [21] Later in 1898, Staudenmaier modified Brodie's method and used nitric and sulphuric acid in 1:4 in an ice bath, which is considered a safer method [22] but toxic gases are still an issue. After several modifications, Hummer developed a new method that is more common for the preparation of graphene oxide using NaNO₃, KMnO₄, and H₂SO₄. Moreover, graphene oxide (GO) is prepared from high-purity graphite powder [23]. In this

method, 3g graphite powder and 1g NaNO_3 are mixed with 100 ml sulphuric acid and stirred for several minutes. After that 12g KMnO_4 is added slowly into this solution at 20°C . Then this mixture is stirred for 4-5 hours until the solution becomes dark green. After that, 140 ml of deionized water is added to this solution and stirred for 30 minutes at 98°C . Hydrogen peroxide (40 ml) is added drop by drop for removal of KMnO_4 and cooled down using an ice bath. After cooling, 10 ml of hydrochloric acid and 250 ml of deionized water are added and stirred for 1 h. The residual is washed 3-4 times with 1M hydrochloric acid and deionized water. The washed GO solution is dried using an oven at $90\text{-}100^\circ\text{C}$ for 24 h to produce GO powder. The prepared GO powder is sonicated and reduced to obtain graphene. Later on, the Hummers method was modified by Tour et. al. in 2010 to eliminate the toxic gases NO_2 and N_2O_4 . They replaced NaNO_3 with potassium permanganate and a mixture of reactions consisting of (9:1) H_2SO_4 : H_3PO_4 for oxidation reaction [24].

Graphene can also be obtained through the reduction of the conjugate structure of GO, referred to as reduced GO (rGO). Also, the electrically insulated GO is converted to the conductive by the removal of the oxygen atom to develop a partial sp^2 character. Reduction of GO is done by thermally, chemically, electrochemically, or green synthesis route [25].

ii) *Unzipping Carbon Nanotubes*

In this technique, sulphuric acid and KMnO_4 are used for cutting multi-walled carbon nanotubes (MWCNTs) in a longitudinal direction, followed by the chemical reduction of the oxidized graphene produced through ammonium hydroxide and hydrazine monohydrate. The graphene nanoribbons are developed using this method, and the developed nanoribbons are reduced by different chemicals. These nanoribbons are conducting in nature, however, due to the presence of oxygen defects, these graphene nanoribbons display electrical properties slightly inferior to graphene [11]. The MWCNTs were unzipped by various

experimental methods such as a mixture of acid, a catalytic cutting method, electrical zipping, and H-based zipping, etc.

2.4 Other Methods.

There are several other methods to produce graphene such as arc discharge of graphite, electron beam irradiation of PMMA nanofibers, thermal fusions of polyaromatic hydrocarbons, and conversion of nanodiamonds.

In addition, different types of graphene-based materials such as graphene nanoribbons, graphene quantum dots, and graphene foam or aerogel can be fabricated. Particularly, graphene foam is a 3-dimensional honeycomb structure that possesses many interesting properties such as low density, high open porosity and high surface area, good mechanical strength, excellent electrical and thermal conductivity, and good chemical and corrosion-resistant. These extraordinary properties make graphene foam a promising candidate for many engineering applications.

3. Applications of Graphene

Graphene is a wonderful material that holds promising properties such as high electron mobility which is ~ 100 times or even higher than silicon that is commonly used in electronics, electrical conductivity higher than copper, high transmission (about 97.7%), high thermal conductivity even higher than 3-dimensional diamond, high impermeability, and many more. These properties make graphene and graphene-related materials promising candidates for numerous applications.

High Strength: The mechanical strength of graphene can reach ~ 130 Giga Pascal (130 Giga Pascal = 13256310768.713 Kg/m^2) which is about a few hundred times higher than steel. The hexagon lattice developed by sp^2 carbon atoms restricts in-plane deformation depicting impressive mechanical strength. So, graphene can be used as fillers in polymers and metals to exceptionally enhance their mechanical strength. Numerous studies have been performed on the mechanical properties of graphene reinforced composites and their mechanical strength is generally

analyzed through stress-strain curves obtained by tensile tests. The mechanical strength of the graphene and GRMs reinforced composites depends on filler geometry, dispersion, number of graphene layers and size, the interaction between matrix and filler, and the fabrication process. Gong et.al studied the effect of how the number of graphene

layers influences the mechanical properties of polymer matrix [34].

Kim et al designed nanolayered composites with alternate layers of single-layer graphene and a layer of metal (copper or nickel) and found high mechanical strength of 1.5 GPa and 4 GPa in graphene-copper and graphene-nickel structures, respectively [35]. Jeon et. al

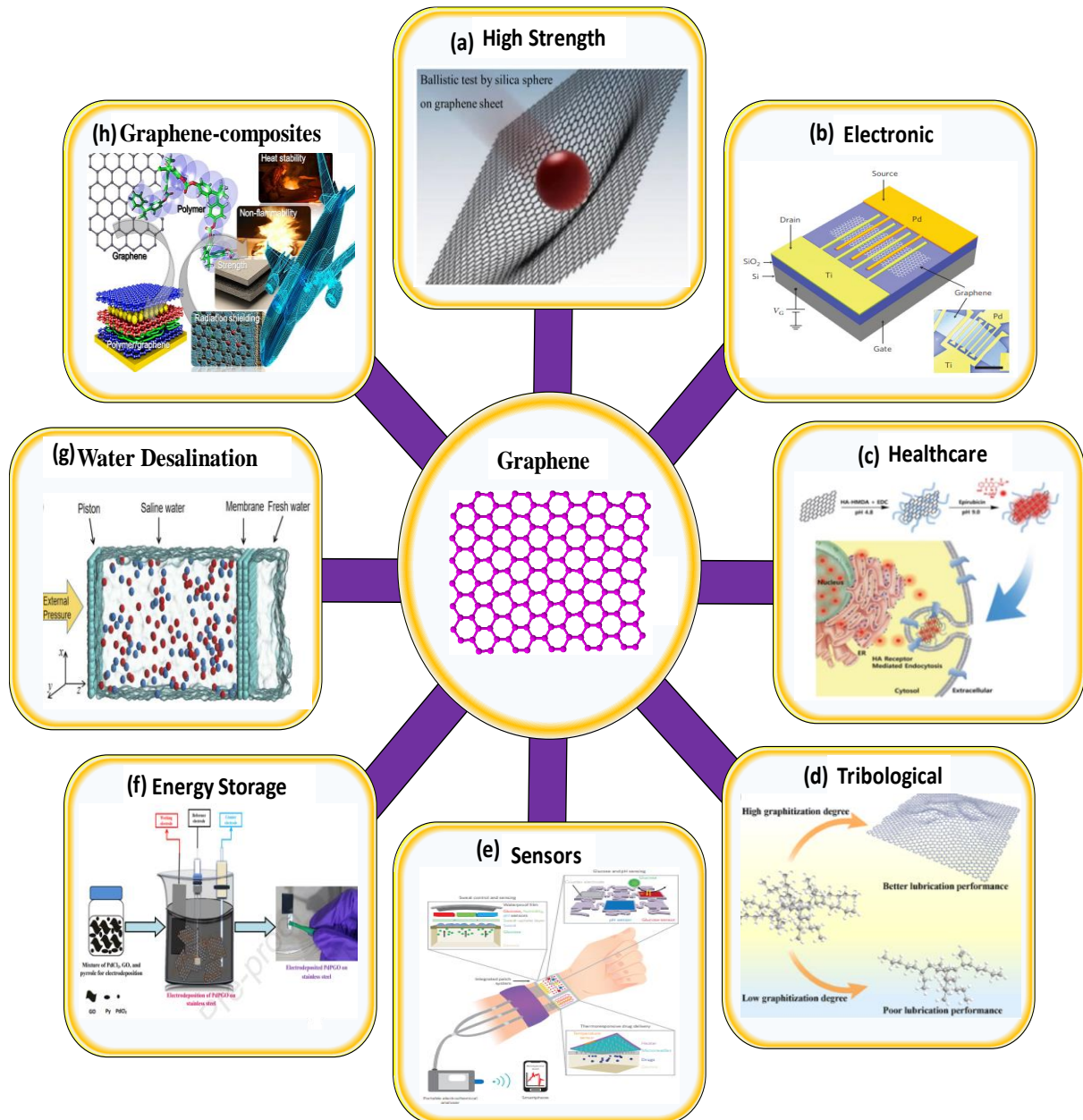


Figure 4: Schematic representation of graphene in different applications (a) miniature ballistic tests by firing tiny silica spheres at sheets of graphene [26] (b) metal–graphene–metal (MGM) photodetectors with asymmetric metal contacts [27](c) Schematic illustration for the preparation process of epirubicin/ NGO–HA complex and the target specific delivery of the complex to cancer cell via HA receptor mediated endocytosis [28] (d) illustration of the relationship between graphitization degree and lubrication performance [29] (e) sweat sensor [30] (f) schematic depiction of the synthesis and electrochemical performance of PdPGO for supercapacitor [31] (g) Side view of an individual simulation system, composed of a piston, a membrane with a nanopore and two water boxes. The left water box is saline while the right one is fresh water[32] (h)polymer-graphene nanocomposite in aerospace [33].

investigated the effect of the size of graphene nanosheets (1 μm , 750 nm, 250 nm, and 20 nm) on the mechanical properties of polymer nanocomposites and found that effective interfacial adhesion is greater for large size graphene nanosheets due to large contact area that influences the mechanical properties [36]. However, the concentration percentage of the graphene and GRMs for both polymer and metal matrix goes through the threshold value up to which the mechanical strength increases, and after that distortion of properties occurs. In civil structures, the application of 0.05 wt. % of graphene resulted in 8%, 79%, and 9% enhancement of compressive strength, tensile strength, and Young's modulus of ordinary Portland cement, respectively [37]. The graphene reinforced shape memory polymers [38], shape memory metallic alloys [39], automobile components, and engineering components are some examples where graphene has been exploited to enhance the mechanical strength and other mechanical properties of the systems. For example, Krishnamoorthy et. al designed a siloxene-graphene heterostructure electrode-based symmetric supercapacitors that delivers a maximum power density of 15 000 W kg⁻¹ and high energy density (55.79 Wh kg⁻¹) [40]. Le et al. designed aligned graphene/carbon nanotube fibers that possess high mechanical strength and excellent electrical properties [41].

Electronic Applications: Graphene displays extremely high carrier mobility that can be reached to about 10^5 - 10^6 cm²V⁻¹s⁻¹, which is about 2 to 3 orders of magnitude higher than commonly used semiconductors such as silicon. Thus, graphene has a bright future for electronic applications such as in the development of micro- and nano-electronics devices. It is the potential alternative to silicon technology [42] and its distinct optoelectronic characteristics make it a perfect medium for rapid photodetectors [43], optical modulators [44], plasmonic devices [45], ultrafast lasers [46] etc. A graphene-based transistor can develop faster electronic devices. GRMs,

especially nanoribbons, are appealing structures for logic microprocessors due to high current-carrying capacity, high carrier mobility, and, saturation velocity, thereby enabling high performance at a lower power supply. Moreover, semiconducting GNRs are appealing not just for logic applications but also for low power radio frequency (RF) technologies and a variety of novel devices in quantum informatics, thin-film electronics, and spintronic (such as flexible devices and sensors)[47, 48]. Importantly, in silicon-based CMOS technology, the number of transistors per processor is increased by reducing the gate length. However, conventional CMOS technology is reaching the fundamental limit. Thus, not only the graphene's extremely high carrier mobility important, but also atomic thinness can play a vital role, and together both these properties can enable the development of futuristic high-speed field-effect transistor (FET) technology. Indeed, graphene-based FET has shown exceptional electrical behavior [49-51]. Owing to their high mobility and conductivity, high optical transparency, and sharp edges the graphene, GRMs and their composite have also broad applications in electromagnetic shielding and electronic packaging [52]. Graphene-based touchscreen panels have also been designed [53]. Graphene and GRMs have also been explored for solar power generation owing to their optical transparency and high carrier mobility. In solar cells, graphene has been utilized as a buffer layer, electrode, and electron/hole transport medium material [54]. Sim et. al developed a graphene based CIGS solar cell in which graphene film was coated on the flexible copper foil through the CVD technique and used as a hole transport layer that yielded a power conversion efficiency of $9.91 \pm 0.89\%$ [55].

Healthcare Applications: Microbial contamination is a big problem across the world that affects human health and in severe cases, it leads to the death of humans. The world has just witnessed one such infectious disease viz. COVID-19. Owing to their appealing properties, graphene and graphene-

related materials (GRMs) have shown potential to contribute to the fight against COVID-19 [56, 57]. Graphene and GRMs show antimicrobial and antiviral properties. Thus, graphene and GRMs can be used as fillers in polymeric materials or other biomaterials to boost their antimicrobial properties or can be applied as coatings on surfaces to prevent infection spread. Furthermore, graphene and GRMs display excellent electrical and surface properties. Moreover, their surfaces can be functionalized by various functional groups. These properties of graphene and GRMs make them promising candidates for high-performance biosensors too [58, 59]. The graphene-based biosensors have the potential for fast, precise, and highly sensitive diagnosis of viruses, various biomolecules, etc. A lot of work is underway on this subject across the world. Graphene stimuli responsive materials also snatch the attention of polymeric implants for on demand drug delivery [60]. According to reports, electroactive scaffolds retain their structural integrity while exhibiting regulated drug release in a pulsatile manner when modest electrical voltages are applied at low graphene concentrations (0.2 mg mL^{-1}) [61]. The most fascinating research on GRMs for regenerative medicine applications includes bone, nerve, cartilage, muscle, heart, skeletal, skin, and adipose tissue regeneration [62]. For example, the 3D graphene foams were developed and employed in bone regeneration. Crowder et al. fabricated 3D porous graphene foams by growing graphene on a 3D nickel scaffold and employed the 3D graphene foams as culture substrates for hMSCs [63]. Chen et al. developed graphene enhanced electronic skin (E-skin) for biomedical applications [64].

Tribological Applications: Tribology deals with friction, wear, and lubrication. t of contact sliding systems immensely suffer from high friction and wear. High friction, a force that renders the motion of the object, contributes to a huge amount of energy wastage [65]. A significant amount of energy in automobiles is used to combat friction. On

the other hand, wear is the damage/degradation of the components/systems. Many commercial systems such as automobile components, turbines, MEMS/NEMS devices, nanoscale contact sliding devices, magnetic storage devices, engineering systems, etc., are hugely suffer from high friction and wear. Controlling/reducing friction and wear is essential for increasing the operational lifetime of the components, minimizing energy wastage, reducing economic loss, and saving the environment. Graphene has shown excellent tribological properties despite being just a single-atom-thick material [66]. It exceptionally reduces the friction of a wide variety of surfaces such as silicon, glass, ceramic, gold, mica, steel, etc., and considerably increases the wear resistance. Bilayer and few-layer graphene also show extraordinary tribological properties [66]. Thus, the application of graphene-based overcoats or graphene-reinforced composites can help to increase the operational lifetime of contact sliding components in various commercial systems [67].

Functional and soft robotic systems use graphene-based materials to increase the movement and response of sensors, actuators, and biomedical transplants [68-70]. In graphene composites, graphene addition also increases the thermal conductivity, which helps to increase the heat dissipation at the contact interfaces and reduces wear and deformation [68].

Sensors Applications: Graphene and GRMs are potential candidates for sensing applications. Graphene can attain a large strain without a considerable change in its electrical conductivity.

Thus, graphene-based high-performance strain sensors (in combination with other flexible polymers) can be designed and developed. The prototypes of graphene, GRMs, and graphene/GRMs-polymer composites-based flexible pressure sensors have already been demonstrated. The graphene, GRMs, and their composites-based sensors are crucial for healthcare applications

such as in the development of blood pressure sensors. Kireev et. al developed a wearable, atomically thin, self-adhesive graphene electronic tattoo as a human bioelectronics interface for monitoring blood pressure based on electrical bio impedance [71]. Gao et.al developed a completely integrated sensor array for multiplexed in-situ perspiration analysis [72]. Kang et al. designed a graphene-based wearable thermal patch device that is used for thermotherapy and continuous skin temperature monitoring for self-care [73]. Graphene-based electrochemical sensors have also been developed to detect small biomolecules like uric acid, ascorbic acid, and dopamine in the human body [74, 75]. GRMs have also shown remarkable gas-sensing capability [76]. Graphene-based devices have been developed to detect toxic gases like SO_x , CO_x , and NO_x [77]. Moreover, Hu et.al used graphene-based plasmon devices for the detection of gas molecules such as SO_2 , NO_2 , N_2O_2 , and NO [78].

Energy Storage: In contemporary society, there is a pressing demand to enhance the energy and power densities of electrochemical energy storage devices. Graphene has recently brought about significant advancements in portable electronics and electric vehicles by offering superior methods for electricity storage [79]. Battery and capacitors are important ways of storing energy; they follow the electrochemistry mechanism(s) to store the energy. However, there are always challenges that need to be solved for advanced technologies. The lithium-ion battery is commonly used as an energy storage device that uses a LiCoO_2 cathode and a graphite anode. The performance of the battery considerably depends on the properties of electrode materials. Since graphite anode has a low specific capacity (372 mAh g^{-1}), there is always a search for efficient anode material for Li-ion batteries. Graphene, rGO, and their composites with metal and metal oxides have been employed as anode material for Li-ion batteries. For example, Cu-supported graphene can reach specific capacities of 1500

mAh g^{-1} . Graphene and its hybrid with metal oxide are also proposed to be used as a current collector at the cathode, replacing conventional Al current collectors. There are many other components of Li-ion batteries where graphene and its composites with other materials can show promising properties and replace conventional materials. Furthermore, the combination of an aluminum anode with a cathode featuring high energy and power densities shapes the trajectory of aluminium-ion battery technology [80]. The outlook for the Al-graphene pairing appears promising, provided immediate and focused efforts are directed toward overcoming the inherent technological challenges. While the concept of Aluminium-Ion Batteries (AIB) was initially conceived in the early 1970s, it gained significant attention in 2011 when the secondary nature of an Al- V_2O_5 cell at ambient temperature was demonstrated [81, 82]. The Al-graphene cell demonstrates the potential to provide an unexpectedly high power density (approximately 175 kW kg^{-1}), comparable to supercapacitors, while simultaneously maintaining an energy density (around 66 Wh kg^{-1}) higher than that of a lead-acid battery [83]. Instances exist where combinations of energy and power densities reach 200 Wh kg^{-1} – 200 W kg^{-1} and 160 Wh kg^{-1} – 50 kW kg^{-1} [84]. Remarkably, the Al-graphene cell achieves an exceptionally long lifespan, enduring up to a quarter-million cycles with minimal loss in specific capacity (approximately 111 mAh g^{-1}) when subjected to an immensely high current rate of 100 A g^{-1} [85].

The supercapacitor is another important device for the giant storage of energy. A supercapacitor contains two electrodes and an electrolyte [86]. Unlike batteries, they function as energy storage devices that exhibit high power performance, featuring rapid charge and discharge times, minimal degradation over extended cycling periods, and environmental sustainability [87]. Nevertheless, these devices are unable to attain the elevated energy density achievable with batteries. Supercapacitors can be categorized into two types based on their

charge storage mechanisms: electric double-layer capacitors (EDLCs) and pseudocapacitors, as well as hybrid combinations thereof [88]. For the development of a good quality supercapacitor, the surface area of the materials must be as high as possible and the separation between the charges must be minimum. In particular, for electrodes, the materials should have high electrical conductivity and many other excellent physicochemical properties. Graphene, GRMs, and their composites have been explored for supercapacitor applications. Graphene has garnered considerable attention in the field of supercapacitors due to its exceptionally high surface area, reaching up to $2,630 \text{ m}^2 \text{ g}^{-1}$ [89]. In the realm of energy storage, graphene emerges as a promising candidate for the next generation of supercapacitor electrodes owing to three primary factors. Firstly, its unrivaled surface area of $2630 \text{ m}^2 \text{ g}^{-1}$ and remarkably low theoretical density of 2.28 g cm^{-3} grant the material a dual advantage of high packing density capability and an expansive specific surface area, facilitating efficient interaction with electrons and ions. Secondly, graphene exhibits exceptional electrical conductivity, featuring high motilities of up to $200,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at room temperature. This characteristic enables rapid electron and ion transfer across various device interfaces, such as electrode/electrolyte and electrode/collector. Additionally, the high electrical conductivity allows graphene to serve as both an active material and a current collector, eliminating the need for additional materials like binders and additives. Lastly, graphene demonstrates notable mechanical strength, boasting Young's modulus of 1 TPa and showcasing reversible strain up to 25%. This strength makes graphene suitable for applications in flexible and printable electronics while maintaining high capacitance retention [10, 89]. These graphene-based materials considerably change the electrode and electrolyte properties and suitably tailor the performance of supercapacitor. Graphene and GRMs have the high surface area and they are ultrathin

both these properties make them potential candidates for electrode development. Owing to its large surface area and excellent conductivity, graphene was employed as an electrode for supercapacitors for the first time by Ruoff's research group [10]. Subsequently, efforts have been consistently directed towards strategies aimed at minimizing the agglomeration of graphene sheets to optimize both the accessible surface area and the development of extensive supercapacitors. Among the successful methodologies employed thus far is the utilization of graphene foam (GF) synthesized through chemical vapor deposition (CVD) [90-92]. Graphene exhibits a capacitance significantly lower than the theoretical capacitance values of 550 F g^{-1} for supercapacitors and 744 mA h g^{-1} for lithium-ion batteries [93]. The charge storage mechanism observed in pristine graphene supercapacitor materials falls under electrical double-layer capacitance (EDLC), wherein the charge is physically stored through the adsorption of electrolyte ions onto the graphene surface [94]. When the entire specific surface area (SSA) of $2630 \text{ m}^2 \text{ g}^{-1}$ is fully utilized, graphene electrode materials can exhibit an electrical double-layer capacitance (EDLC) of 550 F g^{-1} . further to enhance this capacitance doped and functionalized graphene, and graphene composites have been engineered to incorporate extra pseudocapacitance [95, 96]. Achieving the theoretical charge storage limit of graphene electrode materials for application in electrochemical energy storage devices demands extensive efforts in the systematic design of the structure and chemistry of graphene materials.

Water desalination: Graphene demonstrates high impermeability against contaminants and allows the water to pass through it. This property of graphene and GRMs enables them to be promising candidates for water purification applications [97]. Graphene and GRMs are used not only for drinking water desalination but also effective in the purification of the sea and industrial waste water [98, 99]. Water desalination requires

effective ion sieving as well as ultra-fast water flow for continuous supply, in which graphene and GRMs possess an extensive advantage through nanofiltration membranes with sub-nano to atomic-scale capillaries (6 Å) [100, 101]. Graphene and graphene possess antimicrobial properties that improve water purification quality [102]. Moreover, various molecules and methods are utilized to control and modify the graphene and GRM pore size for selective ion sieving. For example, Chung et al modified GRMs (GO) with ethylenediamine, which was used for the separation of Pb^{2+} , Ni^{2+} , Cd^{2+} , and Zn^{2+} with obtained maximum rejection up to 95.7, 96.0, 90.5, and 97.4%, respectively and attained the water permeability of $\sim 5.0 \text{ L m}^{-2} \text{ h}^{-1} \text{ bar}^{-1}$ [103], Gong et al confined the GRMs (GO) interlamination to 0.71 nm with 99.9% restriction of organic ion NaCl. [104] Likewise, Chen et al demonstrated a scalable production of subnanometer porous ultrathin graphene membrane by subsequent reduction and carbonization of the GO nanosheets and polymer on the ceramic porous substrate; they achieved a water evaporation flux of 49.8 ± 1.5 – $472.3 \pm 14.2 \text{ L m}^{-2} \text{ h}^{-1}$ and 99.99% NaCl rejection at 20–70 °C [105]. Salt dye separation from water is also a big concern, Padmavathy et al exploited a GRMs-based system for various dye separation and divalent ion rejection [106]. Although, the graphene and GRMs-related framework performs better in water desalination their commercialization and scalability are the most critical aspect, along with the large quantity and high quality production of graphene.

Graphene-composites: Composites of graphene with metals and polymers display enhanced properties due to the application of graphene. The introduction of graphene and GRMs improves various properties of metals and polymers such as electrical properties (increase the electrical conductivity) [107], thermal properties (increase the thermal conductivity) [108], mechanical properties (increase the mechanical strength) [109], tribological properties (reduce the friction and wear) [110], corrosion property (reduce the

corrosion) [111], shielding properties (enhance the electromagnetic shielding) [112], and so on. Thus, graphene-metal and graphene-polymer composites are promising candidates for many commercial applications.

GRMs are majorly investigated in most graphene-polymer composites considering their low cost and high yield production. GO enhances the mechanical and thermal properties of hydrophilic polymers like POP [113] and PVA [114]. Considerable work has been carried out on amination [115], esterification [116], isocyanate modification [117], and polymer grafting [118] for the functionalization of GO by forming chemical bonds with the carboxyl and hydroxyl groups to enhance the applications of GO [119]. As polymers are mostly electrically insulating, reduced GO can significantly increase its electrical conductivity [120], but agglomeration or restacking causes difficulty in composite fabrication. CVD graphene as a filler offers various π interactions ($\text{C}-\pi$, $\pi-\pi$, $\pi-\text{H}$, etc.) because of plenty of π electrons on the CVD graphene that results in the ample amount of interfacial interaction with polymer matrix [121]. Yan et al successfully synthesized vertically aligned graphene nanowalls (GNWs) which were covalently bonded by high-quality CVD graphene nanosheets; this filler yielded high thermal conductivity ($12.8 \pm 0.77 \text{ W m}^{-1} \text{ K}^{-1}$) of polyvinylidene fluoride (PVDF) at a low filler content of 4.0 wt.% [122].

Acknowledgments: The authors wish to thank the Director, CSIR-AMPRI, for his kind support. The authors also wish to thank Scientists of CSIR-AMPRI for providing their input on graphene related literature.

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