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Review

Application of graphene/graphene-oxide: A comprehensive review

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Abstract: The remarkable mechanical, optical, electrical, electronic, magnetic, and crystal properties of 2D "graphene" and "graphene-oxide (GO)" among the carbon nanostructure materials provide a variety of practical uses in the fields of electronics, energy conversion and storage, biomedical sciences, environmental protection, coating technology, and the electrical and magnetic fields. I reviewed and presented more than a hundred applications in the field of "graphene and GO" in this study and highlighted the advantages in scientific and technological research. Graphene and GO–have a wide range of applications due to their unique properties. Graphene's excellent electrical conductivity makes it suitable for transparently conducting electrodes in touchscreens, displays, solar cells, transistors, and other electronic devices while GO's transparency and conductivity make it suitable for conductive transparent coatings. Graphene's sensitivity to various stimuli makes it useful for developing gas sensors, biosensors, and other detection devices. Graphene's high surface area and conductivity make it a promising material for batteries and super-capacitors, whereas GO can be used in energy storage devices, such as super-capacitors. Graphene biocompatibility and ability to be functionalized make it suitable for drug delivery, tissue engineering, and other biomedical applications, whereas GO can be used in drug delivery, gene therapy, and biological sensing due to its high surface area and biocompatibility. Both graphene and GO can be used in ultrafiltration and nano-filtration membranes to improve water purification efficiency.

Keywords: graphene; graphene-oxide; nanotechnology; bioengineering; biomedical

1. Introduction

Graphite (sp^2) and diamond (sp^3) are two allotropes of carbon, meaning they are different structural forms of the same element. Diamond-like carbon (DLC) is a class of amorphous carbon materials that exhibits some properties similar to diamond with <75% sp^3 hybridized carbon atom. Graphene, a single layer of sp^2-hybridized carbon atoms extracted from graphite and organized in a two-dimensional (2D) honeycomb lattice, has been one of the most researched materials for the past 20 years. Spintronics, electronics photonics, electrical, magnetic, catalysis, energy storage, and biomedicine are just a few of the fields [1–5] that have used graphene because of its unique structure and characteristics [6–8]. Conversely, graphene-oxide (GO), a derivative of graphene, is a multilayer substance with many oxygen-containing functional groups, such as carboxyl, carbonyl, epoxy, and hydroxyl groups. Affixed to its carbon lattice, GO is applied in fuel cells [9], electrochemical sensors [6–8], nano-catalysts [4], nano- sensors [5], voltametric sensors, conductive electrodes, light emitting diodes, and photovoltaic cells [10,11]. Because GO may bond with other molecules, it can be used for medication delivery, biosensing, and bioimaging. Numerous review articles concerning the production of graphene and GO, as well as their adaptable qualities [12–16] and various applications in other fields, can be found elsewhere [17–19]. Graphene is an exciting material [12] because of its high specific surface area ≈2630 m^2g^{-1}, high intrinsic mobility (≈200000 $cm^2V^{-1}s^{-1}$) [13], high Young's modulus ≈1.0 TPa [14], higher thermal conductivity (≈5000 $Wm^{-1}K^{-1}$) [15], high optical transmittance ≈97.7%, high flexibility, and good electrical conductivity. These properties make graphene a valuable and exciting material [12] for different applications. Graphene has been experimentally studied for over a few decades on their transport properties deposited on SiC [16,17], large area graphene grown on copper (Cu) substrates [18], and micromechanically exfoliated layers [16] among other works addressing the use of chemically modified graphene to create novel materials [19] for other applications. There are practically endless ways to alter and/or functionalize the carbon backbone of graphene [20]. On the other hand, the GO is formed by functionalization of graphene with oxygen-containing chemical groups, has a large surface area, mechanical stability, and tunable properties. GO has emerged as a precursor with potential to enable the large-scale, cost-effective manufacturing of graphene-based products [19] and offers the possibility of producing chemically modified graphene on a commercial scale [21]. A comparison between synthesis method, product, basic properties, and applications are listed and given in Table 1.

Table 1. Comparison between synthesis method, product, basic properties, and application.

Synthesis method	Product	Properties	Application
Mechanical exfoliation	Few-layer graphene (≈10 μm)	Electron mobility ≈ 10,000 cm^2/Vs	Hall bar devices
Electrochemical exfoliation	Graphene nanosheets (GNS) (500–700 nm in size)	Conductivity 13.84 S/m	GNS/polystyrene composites
Metal-organic chemical vapor deposition (MOCVD)	Monolayer graphene	Optical transmittance >97% and sheet resistance of 450 ± 47 W/sq	Transparent conducting electrode
Hummer's method	reduced graphene oxide (rGO) (≈1 μm)	Self-healing efficiency 89% and ultra-high toughness of 141.19 MJ/m^3	PU/graphene nano-composite for micro-plastic removal from water
Mechanical exfoliation and interface functionalization	Graphene nanosheets (thickness 2.4 nm)	Elastic strain 110%	Artificial skin
Wet-jet milling/liquid phase exfoliation	Single/few-layer graphene flakes	Efficiency at 12.5% and 250 W power output	Solar cell
Chemical vapour deposition (CVD)	Few-layer graphene	85% optically transparent 85% and conductive	Graphene tattoos
Ethanol-assisted reduction treatment	rGO	Young's moduli ≈ 1100 kPa	Treatment of skin cancer
Freeze-drying	GO aerogel foam	Conductivity 4.12×10^{-4} S/cm	Solid state battery
Gas phase synthesized graphene	Single to few-layer graphene	Water contacts 153.0 ± 3.0	Super-hydrophobic coating
Electrophoretic deposition	Graphene nanosheets	Tensile strength 518 MPa, and bending strength 477 MPa	Super capacitor
Mechanical exfoliation	Graphene flakes	Mobility 130,000 cm^2/Vs	Spintronics
CVD	Monolayer graphene (0.34 nm)	On/Off ratio 1.02×10^5	Transistor
Micro-fluidized technique	Graphene inks	Resistance ≈ 49 Ω/cm	E-textile
Flash Joule heating	Graphene sheets (size 13.8 nm)	34% increase in tensile strength and 25% in low-frequency noise absorption	Polyurethane foam composite

2. Synthesis of graphene and GOs

Graphene synthesis is the process of creating or removing graphene from graphite. The structure and characteristics of graphene are influenced by the types of synthesis process. Graphene comes in single, double, and multiple layer varieties that are made using different procedures. These layers are used in a variety of scientific and technological domains. Different methods of graphene and GO synthesis are reported by different research groups [1,21–23]. Growth of epitaxial graphene is the main method used to manufacture "pristine" graphene [22]. During large-area growth on SiC wafer surface at high temperature (>1300 °C), Si can be evaporated in either ultra-high vacuum [22] or atmospheric pressure [23] to produce wafer-size graphene with carrier mobility values of around 2000 $cm^2V^{-1}s^{-1}$. Huge area monolayer graphene has been produced via Cu-sheets [18]. In theory, this procedure can be extended to create "endless length, very large width" by exposing appropriate metal foils to carbon, which can result in either monolayer or multilayer surface deposition. With possible uses in nano electronics, the direct development of graphene on metal oxide surfaces is an interesting problem. The production of "high quality" electrically isolated graphene using micromechanical exfoliation can be used for basic transport physics research and other areas that have demonstrated the potential significance of graphene for a broad range of fundamental investigations and applications. Usually, it yields graphene "particles" with lateral sizes between tens and hundreds of micrometers. Physicists were urged to try methods such as using "tipless" atomic force microscopy (AFM) cantilevers to rub lithographically patterned pillars and using scotch tape to make exceedingly thin graphite platelets [24]. Arc discharge synthesis of multi-layered graphene [25] and substrate-free gas-phase synthesis of graphene platelets in a microwave plasma reactor [25] are two other methods that have been documented. A large-scale production of high-carbon-purity "powdered" graphene by thermal CVD processes may provide sufficient material for a range of possible applications beyond fundamental research. Graphene on metal surfaces can be produced by hydrocarbon breakdown or surface segregation of carbon. Graphene can be produced only using this process if the as-grown material can be moved from the metal substrates to other substrates. Despite its apparent simplicity, this has been accomplished only for multilayer and non-uniform films with Ni [26–28] and uniform monolayer graphene with Cu [18]. To suppress carbon precipitation during cool-down, CVD of methane under atmospheric pressure was used to form few-layer graphene films on polycrystalline Ni foils by regulating the metal substrates' cooling rate [28]. The production of few-layer graphene films over thin Ni films also lowered the amount of precipitated carbon [26,27]. Instead, CVD of methane was used to create large area films with >95% as monolayer graphene on Cu foils by taking advantage of the incredibly low solubility of carbon in Cu [18]. Enhancing the synthesis and transfer quality of graphene produced by CVD to any substrate would be ideal. Graphene and graphene-based materials are also frequently synthesized or deposited using other techniques, such as fast thermal annealing and electrophoretic deposition (EPD) [29]. GOs are produced when graphite is exfoliation in solvents. Graphite powders in organic solvents, like N, N-dimethylformamide (DMF) or N-methyl-2-pyrrolidone (NMP), are typically subjected to high intensity ultrasound to create GO dispersions that produce individual layers of graphite oxide [30]. Spin coating, spray coating, dip-coating, drop-casting, and layer-by-layer deposition are some of the many solvent-based techniques. Numerous studies have been published on the synthesis of reduced GO platelets and GO platelet dispersions made from GOs [31]. Three processes are commonly used to synthesize GO: the Brodie [32], Staudenmaier [33], Hummers [34], or a mixture of these.

These methods cause graphite to oxidize to differing degrees. Brodie and Staudenmaier used potassium chlorate ($KClO_3$) and nitric acid (HNO_3) to oxidize graphite while Hummers used sulfuric acid (H_2SO_4) and potassium permanganate ($KMnO_4$). Graphite made by intercalating graphite with strong acids such as H_2SO_4, HNO_3, or $HClO_4$ has also been used as a precursor to the subsequent oxidation to GO [35]. GO is hydrophilic due to its polar oxygen functional groups; it may be exfoliated in a range of solvents and disperses especially well in water [36]. The mechanical exfoliation is a very simple cost-effective option to synthesize the GO. The two methods for dispersing GO platelets are stirring and, more frequently, sonicating the material in a solvent. Various reducing agents have been employed to chemically decrease the resulting colloidal dispersions, such as hydrazine [37], hydroquinone [38], sodium borohydride ($NaBH_4$) [39], and ascorbic acid [40]. Heat treatment reduction has been marketed as an economical and effective method that produces "GO" material with a BET surface area of 600–900 m^2/g. Electrochemical reduction has been demonstrated to be an effective technique for eliminating oxygen functional groups from GO [41]. Chemical reduction using $NaBH_4$ and H_2SO_4 treatment prior to thermal annealing produced graphene platelets with high carbon purity. The liquid phase exfoliation technique is one of the many methods for producing GO. It is suitable to produce highly effective contemporary electronic gadgets and is used for the synthesis and concentration augmentation of graphene. The general procedures for producing graphene are schematically illustrated in Figure 1 and their merits/demerits listed in Tables 2 and 3.

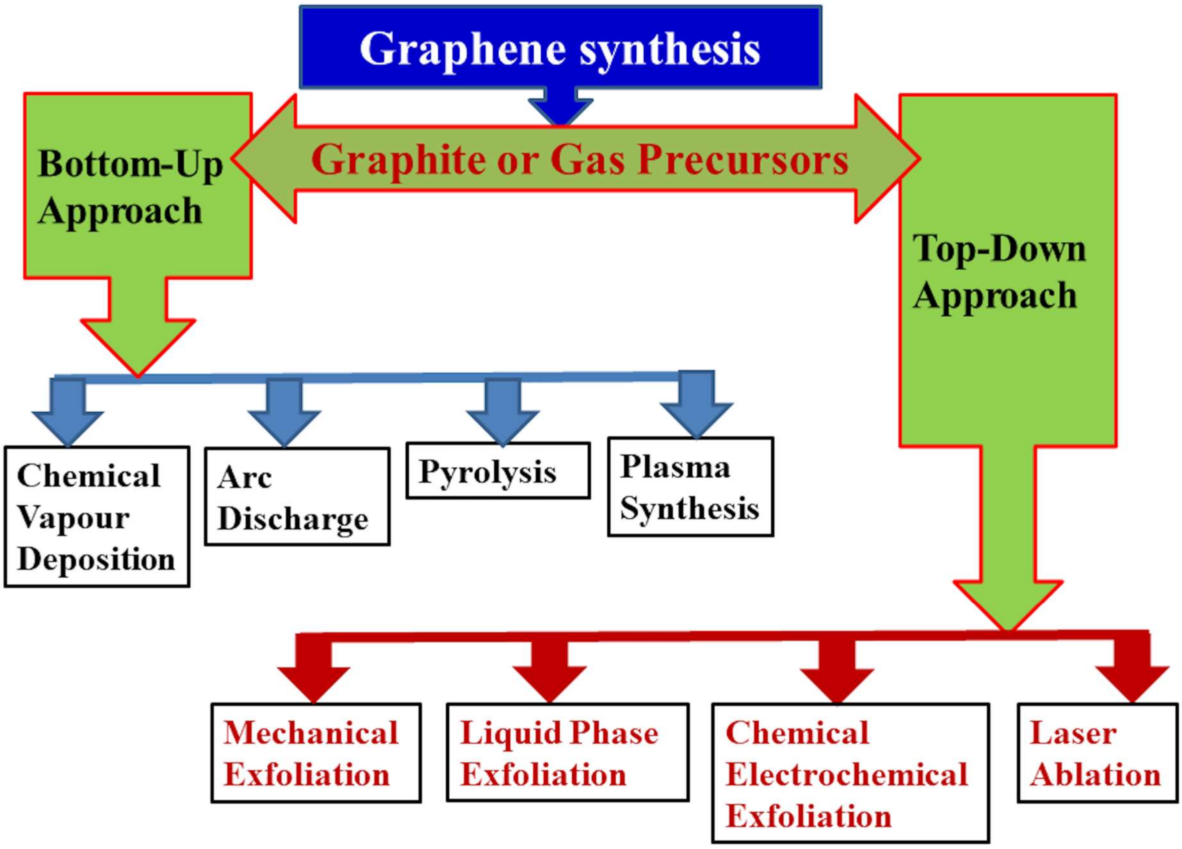

Figure 1. Different methods for graphene synthesis.

Table 2. Merits and demerits of different synthesis methods for graphene.

Method	Thickness	Lateral	Advantage	Disadvantage
Micromechanical exfoliation	Few layers	µm to cm	Unmodified and large size graphene sheets	Very small-scale production
Electrochemical exfoliation	Single to few layers	500–700 nm	High electrical conductivity of the functionalized graphene	High cost of ionic liquids
Graphene exfoliation	Graphene platelets	0.34 to 100 nm	Higher exfoliation yield	Low current density
Arc discharge	Mono-, Bi-, and few layers	100 nm–few µm	Can produce~10 g/h of graphene	Low yield graphene, carbonaceous impurities
Direct sonication of graphene	Both single and multiple layers	µm	Inexpensive and unmodified graphene	Low yield
Reduction of carbon monoxide (CO)	Multiple layers	Sub-µm	Un-oxidized sheets	Contamination with α-Al_2S and α-Al_2O_3
Epitaxial growth on Si-C	Few layers	Up to cm size	Very large area of pure graphene	Very small scale
Unzipping of carbon nanotubes	Multiple layers	few µm long nano ribbons	Size depends on the starting nanotubes	Expensive and oxidized graphene
CVD	Few layer	Very large (cm)	Large size; high quality	Small production scale
Confined self-assembly	Single layer	100's nm	Thickness control	Existence of defects
Reduction of GO	Multiple layers	Sub µm	Un-oxidized sheets	Contamination with α-Al_2O_3 and α-Al_2S

Table 3. Merits and demerits of different synthesis methods for GO.

Method	Oxidants	Toxicity	Advantages	Disadvantages
Brodie method	$KClO_3$, HNO_3	Yes	-	•Weak acidity. •Soft dispersibility in basic solutions. •Small size, limiting thickness and providing an imperfect structure
Staudenmaier method	$KClO_3$, ($NaClO_3$), HNO_3, H_2SO_4	Yes	-	•Time-consuming and dangerous method. •Addition of $KClO_3$ generally takes longer than a week and CO_2 evolved, thus making necessary to remove an inert gas. •The risk of explosions is a constant danger.
Hummers method	$KMnO_4$, H_2SO_4, $NaNO_3$	No (NO_x is released)	Higher oxidation degree than that obtained in Brodie or Staudenmaier methods	•It is considered than the oxidation is incomplete. •Separation and purification processes are tedious process. •Highly time-consuming process.
Modified Hummers method	$KMnO_4$, H_2SO_4, $NaNO_3$, $KMnO_4$, H_2SO_4	No (NO_x is released)	Improved level of oxidation and, therefore, product performance.	•Separation and purification processes are tedious process. •Highly time-consuming process.
Improved Hummers method	$KMnO_4$, H_2SO_4, H_3PO_4	No	•Defects in the basal plane are reduced. •Larger amount of oxidized graphite is provided. •The degree of reduction provides an equivalent level of conductivity when compared to other methods. •Best process yield compared to Brodie, Staudenmaier and Hummers method. •Environmentally friendly, toxic gases are not generated during the preparation. •The product has a more organized structure compared to graphite oxide obtained by Brodie and Staudenmaier methods.	•Separation and purification processes are tedious process. •Highly time-consuming process.

3. Different applications of graphene and GO

The mechanical, chemical, thermal, electrical, and electronic properties of graphene materials are the major causes of their attraction and extensive applications [29]. Electronics, energy storage, sensors, coatings, composites, medicinal devices, and many other fields are among the many possible uses for graphene. Because of its biocompatibility, it is a desirable material for tissue engineering and drug delivery applications [29]. GOs/r-GO, which are derivatives of graphene, are highly utilized in electrochemical deoxyribonucleic acid (DNA) biosensors [2,3], recyclable nano-catalysts [4], electro-analytical nano- sensors [5], electrochemical sensors [5–7], fuel cells [8], and voltametric sensors [10] in addition to graphene (monolayer, bilayer, and few-layer graphene) applications. Despite the large number of graphene and GO/r-GO applications, research gaps exist, including improving large-scale, high-quality production of graphene, controlling the band gap in graphene for electronic applications, and further understanding the complex chemical structure and reduction reactions of GO. In addition, improving the interfacial interactions between graphene and other functional materials in composites is crucial for achieving optimal performance. Various research gaps are identified and listed below with a brief discussion.

(a) Production and quality of graphene

Scalability: current graphene production methods, like CVD, are not well-suited for large-scale, cost-effective production of high-quality graphene.

Uniformity: achieving uniformity, defect-free graphene sheets is a challenge, impacting the material's properties.

Transfer methods: transferring graphene to other substrates can be a complex and challenging process, limiting its widespread adoption.

(b) Band gap engineering of graphene

Graphene's zero band gap: unmodified graphene has a zero-band gap, which prevents its use in many electronics applications requiring a band gap for switching and other functionalities.

Modifying the band gap: methods to open a band gap in graphene, such as applying strain, creating ripples, or using nanoribbons, can negatively impact other properties.

Optimizing band gap: research is needed to develop methods for selectively opening a band gap in graphene while maintaining its other desirable characteristics.

(c) GO and r-GO

Structure and reduction of GO/r-GO: the chemical structure of GO is complex and not fully understood, making it difficult to control the reduction process to rGO.

Interfacial interactions GO/r-GO: understanding the interactions between GO/rGO and other materials in composites is crucial for designing materials with specific properties.

Environmental impact: developing environmentally friendly and sustainable methods for GO synthesis is important.

(d) Specific applications

Bio-functionalization: while graphene and GO are promising for biomedical applications, further research is needed to optimize their biocompatibility and effectiveness.

Sensors: developing more sensitive and specific sensors based on graphene and GO requires continued research into material modifications and integration techniques.

Composites: improving the performance of graphene-based composites for applications like gas barrier materials and energy storage devices needs more research into interfacial interactions and material optimization.

However, graphene's exceptional electrical conductivity and flexibility make it suitable material for transparent conducting electrode, touchscreens, and flexible electronic devices. Different applications of graphene and GO are follows.

3.1. Graphene and GO in energy, cells, and battery applications

Graphene and its derivative, GO, are promising materials for various energy applications, including batteries, fuel cells, and solar cells. Their unique properties, such as high electrical conductivity, large surface area, and flexibility, make them suitable for improving energy storage and conversion efficiency [10].

3.1.1. Graphene in solar cells

Solar cells are a kind of photoelectric cell that reacts to sunshine by altering its electrical characteristics to voltage, current, or resistance. It requires the materials that let light through and are conductive. The operation of solar photovoltaic (PV) panels is often hampered by extreme temperature. Recently, new opportunities for accelerating heat dissipation rates in engineering applications have been made possible by graphene and GO's remarkable thermal conductivity. For solar panels, graphene and GO demonstrate superior manufacturing performance and increased durability in the photovoltaic sector [10]. For improving heat dissipation in solar PV panels, cooling methods that employ graphene and GO in a variety of ways are crucial. Examples include graphene-coated neutral density filters (ND), graphene-enhanced phase change materials, graphene-enhanced thermal interface materials (TIM), and graphene nanoplatelets nanofluids. With a graphene-coated ND filter, the focal point temperature was 20% lower than with an infrared filter, and efficiency rose by 12%. Graphene-enhanced TIM reduced temperature rise by 34% when compared to standard TIM. Compared to other nanoparticle-enhanced PCM, using GnP enhanced PCM resulted in a lower average cell temperature and an increase in the power output and efficiency of the solar PV system. On the other hand, the GnP nanofluid raised the power production by roughly 3.0 W by causing the panel temperature to drop by about 170 °C. The peak surface temperature in the graphene nanofluid circulation solar PV system was 35.7% lower than that of the conventional panel. In addition to providing crucial new information regarding graphene's possible application in other multidisciplinary sectors, such as heat pipes and exchangers and solar collectors, these findings have clarified the usage of graphene in assisting heat transport for solar PV cooling [42]. Specifically, organic photovoltaic cells (OPVs) are determined to use graphene to improve the overall performance of electrodes, active layers, interfacial layers, electron acceptors, and photovoltaic systems based on solar cells or solar panels.

3.1.2. Graphene in organic photovoltaic cells (OVPs)

In a OPVs cell, the absorbing layer is made of organic semiconductors (OSCS), which can be polymers or small molecules. Many researchers have used graphene films as transparent electrode counter electrodes for OPVs [43–46]. Moreover, many studies have been conducted on the use of graphene films as transparent electrode counter electrodes for OPVs. Arco et al. [46] developed OVP cells using CVD graphene films and found that the cells' enhanced optical transmission and conductivity were responsible for their exceptionally high-power conversion efficiency (PCE). Graphene was created by Park et al. [47] via CVD, and its PCE was comparable to that of devices with indium tin oxide (ITO). A different work by Liu et al. [48] showed that graphene may not only replace ITO but also enhance electron transport and exciton dissociation in the hetero junction of a solar cell. A promising, cost-effective, and adaptable substitute for OPVs, dye-sensitized solar cells (DSSCs) generate electrons from a light-absorbing dye and has efficiencies greater than amorphous Si-cells [49]. To cut production costs, graphene was tried for use in transparent conducting electrodes; nonetheless, PCE is much lower than that of conventional devices.

3.1.3. Graphene in fuel cells

Fuels cells are producing power and heat. An electrolyte is surrounded by a stack of two electrodes: a positive electrode and a negative electrode. With the use of graphene-based hybrid designs, numerous effective and durable fuel cell energy systems have been created. Following the discovery of graphene and grapheme-oxide materials [50–53], graphene has shown excellent catalytic performance in fuel cell technology for potential fuel cell device applications [50]. For the electro catalytic reduction of oxygen, Kou et al. [51] have created functionalized graphene sheets supported by Pt nanoparticles. Zhang et al. [52] developed graphene/polyallylamine-Au nano composites, which are employed in the electro catalytic reduction of oxygen. Zhang et al. [52] developed graphene/polyallylamine-Au nano composites, which are employed in the electro catalytic reduction of oxygen. Graphene nano sheets (GNS) have also been investigated for use in polymer electrolyte fuel cells due to its increased carbon monoxide (CO) tolerance [53].

3.1.4. Graphene batteries

Applications for lithium-ion batteries have used graphene and its composite materials as innovative electrode materials [54–57]. The Li-ion batteries made of $LiFePO_4$ and graphene composites [57] and found a very little degradation [57], while Li-C batteries have a specific energy of 370 mAh/g [56]. Using the spray drying method, nano-silicon composites encased in lily-shaped graphene sheets were created. CuO/graphene composite materials have a reversible retention capability, according to Mai et al. [58]. To make a Li-ion batteries, $CoFe_2O_4$-graphene nanocomposite has been used that performed exceptionally well in lithium-ion battery applications. For this kind of battery, Wang et al. [59] use a free-standing graphene-Si nano-composite containing graphene. Graphene batteries are built similarly to traditional batteries, using an electrolyte solution and two electrodes to aid in ion and charge transfer. The primary distinction between graphene-based and solid-state batteries is the makeup of either electrode. Even though the cathode is usually switched, anodes can be made from carbon allotropes. Furthermore, compared to lithium-ion batteries (LiBs), graphene batteries are lighter and more compact. Greater charge capacities are also made possible using graphene. Lithium ions can store 180 Wh/kg of energy, while graphene can store up to 1000 Wh/kg.

3.1.5. GO-enhanced light rechargeable lithium-ion batteries

Batteries made of lithium-phosphate (LFP) and lithium-manganese (LMO) has better specific power and thermal stability. Compared to most other batteries, Li-titanate (LTO) batteries have a longer lifespan and work best in colder temperatures while having a lesser capacity. Direct sun charging is an option for lithium-ion batteries. To facilitate energy storage on bright days, efforts have been made to streamline the conventional process for connecting solar panels to batteries. Simplifying solar energy gathering and storage is the goal. Vanadium pentoxide nanofibers make up the cathode of this light-rechargeable battery [60]. By absorbing light, the substance can produce electron pairs and positive charges (holes) in addition to storing lithium ions. While GO encourages the passage of electrons, the poly(3-hexylthiophene-2,5-diyl) (P3HT), with which the researchers mixes the nanofibers, prevents the flow of holes. Boruah et al. [60] made the battery by punching a hole in the cathode side of a coin cell and adding a glass window to enable light to enter. When the device is illuminated, electrons generated at the cathode move through an external circuit to the lithium anode. The battery is charged when lithium ions are released from the pores of the vanadium cathode, move through the electrolyte, and interact with electrons at the anode to produce lithium. Efficiency quantifies how much energy a battery can produce in relation to how much energy it receives from the sun. However, the device's 2.6% efficiency makes it impractical for everyday use.

3.1.6. GO/r-GO as an energy storage device

These materials are being considered for application as electrode material in fuel cells, solar cells, batteries, and double-layered capacitors due to the enormous surface area of GO/r-GO [61]. Fuel storage for hybrid vehicles may benefit from its potential as a hydrogen storage device. The GO/r-GO nanocomposites are used in lithium-ion batteries. In this case, electrically insulating metal oxide nanoparticles (NPs) were adsorbed onto r-GO to improve battery performance [62,63]. Zhou et al. [64] found that Fe_3O_4 on r-GO, as opposed to pure Fe_3O_4 or Fe_2O_3, increases cycle stability and energy storage capacity when utilized as the anode in Li-Ion batteries. Zhou et al. [64] developed high surface area r-GO, reducing GO to build supercapacitors as energy storage devices. Caffeic acid (CA)-rGO performs well in potential energy storage and sensing applications. Bo et al. [65] used CA-rGO composite materials to build electronic gas sensors and supercapacitors.

3.1.7. Graphene in hydrogen storage devices

Hydrogen is an abundant element and one of the main rivals for developing the next generation of clean fuel. Water is the only waste product left over after energy is produced from the combination of hydrogen and surrounding oxygen. Graphene has attracted attention as a material that may be useful for storing hydrogen. Physisorption and chemisorption are two ways that hydrogen can interact with graphene surfaces to form a connection with carbon. Atomic hydrogen chemisorption is advantageous because the binding energy of hydrogen is higher than the chemisorption barrier energy. The formation of "dimers" of H on graphene surfaces is anticipated to produce higher energy than single bound H [66,67]. It is proposed, theoretically, that a novel three-dimensional (3-D) material containing CNTs, the graphene layers act as "pillars" supporting. A layered structure of this type can be produced experimentally by the interaction of hydroxyl groups with bromic acids and GO [68]. One approach uses the Li, Na, and K chemical ornamentation of graphene. Li was shown to have the ability to adsorb up to four H_2 molecules per adsorbed Li on graphene and nanostructured graphene, resulting in a gravimetric density of >10% [69]. Adding other metals, such as Sc, V, and Ti, to graphene to functionalize also improves its capacity to store hydrogen [70]. While having very little Ca atom clustering, graphene nanoribbons decorated with calcium atoms have been shown to adsorb up to 5% of the mass of hydrogen [71]. Tozzini et al. [72] proposed that the curvature of graphene could be manipulated to control hydrogen desorption. They suggested that the stable C–H bonds formed in curved regions of graphene would help prevent hydrogen from dispersing and allow for controlled release. This approach could be useful for hydrogen storage applications.

3.1.8. Graphene in super-capacitors/ultra-capacitors

Graphene is used in batteries and super-capacitors due to its high surface area and ability to enhance energy storage capacity. GO, the derivative of graphene, can also be used in super-capacitors and batteries, especially when reduced to GO (rGO). Graphene and GO/r-GO are commonly suggested as activated carbon alternatives in supercapacitors. Because of their high-power density, rapid charge-discharge cycles, and exceptional cyclic stability, graphene-based supercapacitors have attracted a lot of interest as energy storage devices. Carbon-based materials are widely used as double- layer capacitors due to their exceptional physicochemical properties. Research on supercapacitors has made extensive use of graphene-based composite materials. The EDLC capacitor consists of two porous carbon electrodes electrically isolated from each other by a porous separator [72]. When developing novel electrode materials, graphene is commonly used instead of carbon to create ultra-capacitors [73–75], which have the capacity to store energy, like an ion battery, and withstand tens of thousands of charging cycles.

3.1.9. Graphene and solar panels

Graphene can be utilized to make materials for solar cells that are transparent and conductive due to its exceptional conductivity and transparency. Despite being a very good conductor, graphene has trouble holding onto the electrical current produced inside the solar cell. Scientists are therefore looking for appropriate methods to modify graphene. For example, GO is transparent and less conductive than other materials [76–79], making it an excellent charge collector for solar panels. To achieve these goals, the organic solar panels use conductive ITO as transparent electrodes in combination with a non-conductive glass layer; however, ITO is expensive, difficult to get, and fragile. To improve OPV performance, researchers are investigating the use of graphene in a variety of components, including electrodes, active layers, interfacial layers, and electron acceptors. This is because graphene has been thoroughly investigated as an alternative to ITO in transparent electrodes.

3.2. Graphene and GO in sensor applications

Graphene and its oxidized form, GO, are extensively used in various sensor applications due to their unique properties like high surface area, high conductivity, and flexibility. These materials are employed in biosensors, chemical sensors, gas sensors, and more, offering advantages like enhanced sensitivity and potential for miniaturization.

3.2.1. Graphene as a sensor

Over the past 20 years, a number of innovative sensors have been created using graphene and GO materials [80]. Graphene-based materials are used in various biosensors, including electrochemical, fluorescent, and optical biosensors, enabling the detection of biological molecules. Biomedicine, photo-electrochemistry, electrochemistry, flexible pressure, clinical and biological diagnosis, and environmental pollutant detection are among the fields that use these. During the last several years of the COVID-19 pandemic, research has been conducted on the detection of the viral sensor. Because of their accuracy and dependability in signal detection, these novel graphene sensors can serve as guidance for researchers in the selection and manufacturing of sensor materials. Figure 2 illustrates the various sensor uses for graphene and GO [81].

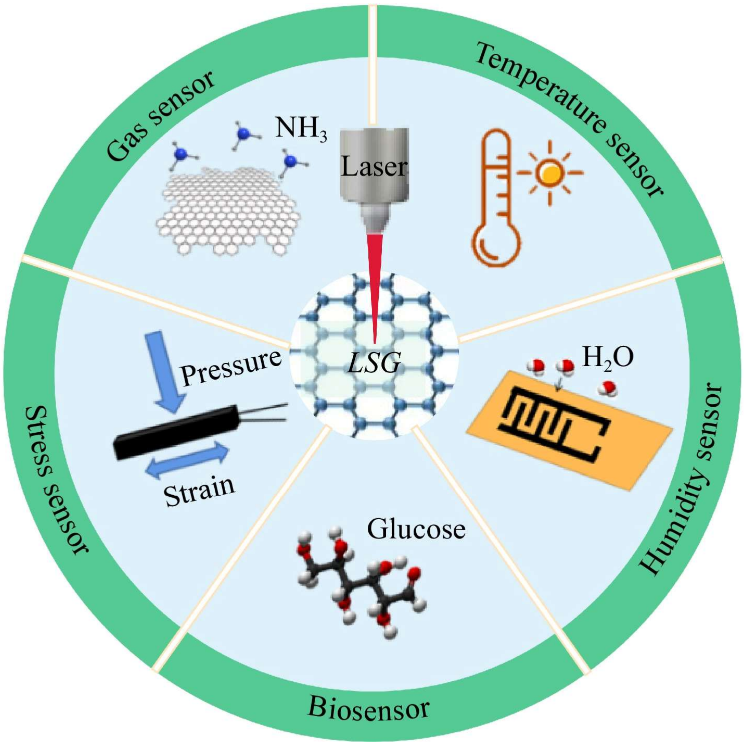

Figure 2. Graphene and GO based different as sensors (Reproduced from Ref. [81] with permission).

3.2.2. Graphene in electrochemical sensors

Materials based on graphene and GO nanocomposites are gaining a lot of interest for use in the development of different electrochemical sensors due to their high catalytic capacity, great stability, and low cost. Fan et al. [82] and Ameer et al. [83] created the graphene/polyaniline (PANI) nanocomposite, which was employed for the differential pulse voltammetry (DPV) approach to determine 4-aminophenol and the very sensitive detection of hydrazine sensors. For non-enzymatic electrochemical uric acid sensors, Du et al. [84] used graphene-modified carbon fiber electrodes. To detect acetaminophen, Chen et al. [85] used a hybrid electrode composed of graphene nano-sheets and carbon nanotubes.

3.2.3. Graphene in gas sensors

The remarkably high surface/volume ratio of graphene indicates promise for gaseous molecule detection. Gaseous molecules cannot readily adsorb onto graphene because its surface lacks dangling bonds. However, by thinly coating graphene with a certain polymer layer, the sensitivity can be increased. A localized shift in electrical resistance results from the concentration brought on by the absorption of the gas molecules. Although this effect is also seen in other materials, graphene performs better due to its low noise and high electrical conductivity, which enable the detection of even the smallest changes in resistance [86]. Based on their structural characteristics, other two-dimensional graphene compounds, such as porous-graphene (PG), GO, and r-GO, provide unique gas sensing capabilities [87]. When gas molecules adsorb on graphene's surface, the surface adsorbates act as either electron donors or acceptors, changing the local carrier concentration and, consequently, electrical conductivity [86]. Graphene doped with B, N, or Si dopants has shown high binding with most common gases (H_2, H_2O, O_2, CO_2, CO, NO_2, NO, SO_2, NH_3, and N_2) [88]. When compared to PG and nitrogen graphene (NG), graphene doped with titanium exhibited better interactions. One of the primary uses of gas sensing technologies in intelligent systems is growing in popularity in both industry and research.

3.2.4. Graphene in optical sensors

In addition to having a large surface area and exceptional high-energy transmission efficiency, graphene is biocompatible. It can be applied to optical sensors for cells, proteins, and small molecules. For the first time, Wang et al. [79] used pure graphene to construct a unique form of sensor that may be used for a wide range of applications. Zhang et al. [89] demonstrated that graphene alone may be used to make flexible, low-cost photo-sensors. The key element of the novel sensor, according to Zhang et al. [89], is its "trapped light" nanostructures, which can hold light from electronic particles for longer than traditional sensors [89]. These sensors benefit from the outstanding optical properties of graphene materials, which have gained popularity recently and provide researchers with much extremely pertinent data. Graphene's remarkable properties have led to numerous scientific and industrial breakthroughs. To create even more tiny optical sensors, researchers are working to shorten the wavelength of light. The optical sensor's graphene can control its thickness using reduced GO, which leads to a high degree of sensor sensitivity. Because of its high sensitivity, the sensor provides a higher resolution. This discovery represents a breakthrough in the development of ultra-small optical switches and sensors.

3.2.5. Graphene UV sensors

The intensity of ultraviolet radiation, a form of electromagnetic radiation with wavelengths longer than X-rays but shorter than visible light, is measured by UV sensors. These sensors are used to measure UV radiation exposure in a variety of contexts, such as ambient and lab settings. They aid in the detection of dangerous UV radiation levels that may cause skin issues or cancer. UV sensors are also used in military operations, environmental monitoring, and optical communication, among other fields. Even while graphene by itself might not have a high photoresponsivity, when combined with other materials, it can be used to create transparent, flexible, affordable, and eco-friendly UV sensors.

Despite its strength, this approach has several disadvantages, including being costly, time-consuming, and taxing on the user.

3.2.6. Graphene security sensors

Graphene is used in the security and armaments industries to improve comfort, safety, and weapon effectiveness. In contrast to the big, heavy sensors that shops frequently use, graphene-based sensors are more affordable, aesthetically pleasing, and flexible without causing circuit damage, and smaller in size. The application of graphene in RADAR systems, lightweight bulletproof jackets, and remotely controlled weaponry with microprocessors is responsible for its uptake in this sector [90].

3.3. Graphene and GO in optoelectronic applications

Graphene and GO have emerged as promising materials in optoelectronics due to their unique optical and electrical properties. Graphene's high mobility, transparency, and flexibility make it suitable for applications like touch screens, light-emitting devices, and solar cells. GO, while initially used to produce graphene, has also gained recognition for its own distinct properties and applications in photonics, electronics, and optoelectronics.

3.3.1. Graphene in optoelectronics

Because of its remarkable electrical and optical properties, graphene has emerged as a material of interest for low-energy telephony and other useful optical applications. Graphene can be incorporated into complementary metal-oxide-semiconductor (CMOS)-compatible technologies to produce silicon-based photonic devices due to its intrinsic characteristics [91].

3.3.2. Graphene in organic light emitting diodes (OLEDs)

When an electric current is applied to an electroluminescent (EL) or OLED light is released. OLEDs use flexible, transparent conductive electrodes called graphene sheets [92]. To increase the brightness efficiency of their OLED devices, Han et al. [92] used CVD graphene films that were deposited on copper foils and subsequently transferred onto polyethylene terephthalate (PET) substrates. More conductance and work function may possibly be linked to the higher brightness seen in graphene films doped with gold.

3.3.3. Graphene as liquid crystal displays (LCD)

Graphene-based terahertz phase shifters were created by Wu et al. [93]. Additionally, Blake et al. [94] created a device using graphene electrodes. It was equivalent to regularly used metal oxides and shown remarkable performance with a high contrast.

3.3.4. Graphene in generating light

When light hits the graphene surface, it slows down and starts to flow at a speed that is extremely comparable to that of electrons. On graphene, photons travel faster. Because of this phenomenon, light can be created by overcoming the electron light barrier [95]. Compared to more conventional light-generating methods like fluorescent or LEDs, this approach is expected to be more efficient, quicker, smaller, and controllable.

3.3.5. Graphene as photo-detectors

Graphene-based photodetectors have received a lot of interest due to their rapid response time and ability to detect weak signals, which are crucial in applications such as optical positioning, remote sensing, and biomedical imaging [96]. The spectral bandwidth is constrained by the absorption [97]. Graphene can absorb wavelengths ranging from the ultraviolet to the terahertz. Consequently, graphene-based photodetectors may operate throughout a much larger wavelength range. Graphene can reach incredibly high speeds due to its tremendous degree of mobility. This mobility affects the response time [97]. Graphene’s potential for high-speed photodetection was demonstrated via an operational communication link running at 10 Gbit/s [97].

3.3.6. Graphene for infrared light detection

Guo et al. [98] have proposed and experimentally proven that the sensitivity can be enhanced by the collective oscillations of charge carriers in graphene plasmons. Guo et al. [98] constructed a device on a CVD graphene wafer using graphene-disk plasmonic resonators coupled by quasi-1D graphene nanoribbons. They observed how the surfaces of the graphene resonators and nanoribbons excited and absorbed high room-temperature infrared plasmons when they exposed the setup to mid-infrared light with a wavelength of 12.2 m. It is also observed a strong correlation between the degree of plasmonic absorption and light absorption, which, thanks to the graphene nanostructures, became an electrical responsivity; reaction times enabled GHz-speed detection. These results show how effective graphene is in converting light into electrical impulses at extremely high speeds. As a result, extremely tiny detectors are now easily included into high-density integrated infrared photonic circuits, which have a variety of uses, such as air quality monitoring, security, and bioassays.

3.3.7. Graphene in photography

One of the most promising materials for developing digital photography and other industries that use optical modulators and photoreceptors is graphene due to its remarkable sensitivity to visible, infrared, and ultraviolet light. In addition to being more lightweight and smaller, camera sensors upgraded with graphene quantum dots (GQDs) can achieve greater resolution than any tiny sensor now on the market. The usage of graphene as a support material to improve photo response is growing. Photo- induced electron transfer in hybrid materials is made possible by its high electron mobility and transparency, which improves performance. GO could function as a photothermal switch by effectively converting near-infrared radiation into heat. For optical applications, such as sensors, photocurrent switches, photodetectors, and photocatalysts, it offers favorable substitutes. Developments in the synthesis and characteristics of graphene-based photo responsive materials were summarized by Chi et al. [99].

3.4. Graphene and GO in electrical applications

Graphene and its derivative, GO, offer various electrical applications.

3.4.1. Graphene as piezoelectricity

Bent graphene can be considered a piezoelectric material because it shows piezoelectric effects. In non-piezoelectric graphene, piezoelectric effects can be produced via selective atom surface adsorption. Ong et al.'s simulations using density functional theory [100] indicate that piezoelectricity is produced when a single graphene sheet is doped with atoms on one side. When graphene is exposed to an external electric field, these ad-atoms cause it to become piezoelectrically sensitive. Due to its similar size to bulk piezoelectric materials, graphene, a type of locally controlled piezoelectricity, is an excellent choice for control and sensing in nanoscale devices [100]. Despite their 2D nature, piezoelectric magnitudes in 2D materials are shown to be comparable to those in 3D materials. Ong et al.'s research [100] clarified a nanoscale-specific designer piezoelectric phenomenon that may provide dynamic control for nanoscale electromechanical devices.

3.4.2. Graphene in thermoelectric applications

The material's excellent electrical conductivity makes graphene a promising candidate for thermoelectric applications. Its high heat conductivity is a major barrier, though. Pure graphene cannot achieve the optimum thermoelectric performance on its own; the intrinsic heat conductivity of thermoelectric materials must be reduced by additions. One possible area of research involves the development of graphene composites with organic or polymer conductors, which have shown some improvements in thermoelectric performance [101]. Electricity is created when two distinct electric conductors or semiconductors come together and receive heat. This phenomenon is referred to as the Seebeck effect or thermoelectric effect.

3.4.3. Graphene as a frequency multiplier

Different quantum tunneling techniques can operate a graphene-based quantum tunneling transistor, and by applying appropriate biases, it can generate voltage-resistance (V-R) curves with varied nonlinear resistance characteristics of the base and emitter voltages [102].

3.4.4. Graphene as an optical modulator

Graphene may be used in optical modulators because of its high carrier mobility (~200,000 $cm^2/(V{\cdot}s)$ at room temperature) and fast modulation speed. Graphene is hence one of the components of ultrafast electronics/photonics devices [103]. Optical absorbance can be altered by varying the Fermi level of the graphene sheet. Within the region of 1.35 to 1.6 μm is a graphene-based optical modulator that has a small footprint (~25 μm^2) and can modulate frequencies at about ~1.2 GHz without the requirement for a temperature controller.

3.4.5. Graphene in speakers and headphones

The speaker uses the vibration of an aerial membrane to transform electrical energy into sound. Membranes are made of graphene, which is renowned for its exceptional rigidity and low weight. As a result, with the same energy input, speaker components made of graphene will vibrate faster than those made of cellulose or PET. Additionally, speakers with graphene drivers will warp less because warping alters the sound output. In essence, graphene drivers are dynamic drivers with graphene acting as the diaphragm. The tiny diaphragm in headphones is reinforced with graphene, which is perfect for energy-efficient (wireless) headphones because of its low weight and low power consumption.

3.4.6. Graphene in deaf-mute communication

Researchers have developed printable conductive 3D graphene structures, which they have incorporated into electronic devices that interpret written and spoken sign language [104]. The development of printed electronics could be accelerated by graphene ink, which is easy to produce and extruded from a syringe. The device makes use of graphene's exceptional conductivity and flexibility. Wearable and bio-integrated devices are staples in medical technology, ranging from adhesive patches that track respiratory rate and pulse to brain- computer interfaces that activate neurons. Because of its exceptional mechanical and electrical properties, graphene a 2D honeycomb lattice of carbon atoms is a major player in the wearable technology space. For complex movement perception, the multi-dimensional sensor's flexibility enables multi-channel analysis. A well-designed wearable graphene aerogel sensor enables the extraordinary ability of gesture language interpretation for gadgets that help with deaf-mute communication or gesture manipulation.

3.5. Application of graphene and GO in nuclear plants

Graphene and GO offer several promising applications in nuclear power plants, primarily in areas like filtration, waste management, and materials for enhanced performance.

3.5.1. Graphene in cleaning radioactive waste in nuclear power plants

Graphene is widely employed in nuclear power plants due to its rapid absorption of radioactive elements in aqueous solutions. Small GO particles are easily dissolved in water and operate as a sort of sponge, absorbing radioactive elements to form lumps that may be removed from the liquid and burned or recycled. This feature of graphene makes it possible to use whole new technologies for industrial liquid cleaning, including that of nuclear power plants. It has been demonstrated that graphene works well as a metal alternative in catalysts. One kilogram of graphene is thought to be capable of removing up to 25 kilograms of a radioactive isotope. The advantages of the approach include its high level of efficacy and simplicity [105].

3.5.2. Graphene in cooling nuclear power plants

During the production process, millions of tons of carbon dioxide are released into the environment by the heavy water (D_2O) needed to cool the nuclear reactors in nuclear power plants. D_2O generation is necessary for the nuclear industry to produce clean energy, but it is an expensive process. It might be feasible to separate subatomic particles in a more efficient and cost-effective manner due to graphene's unique properties. Very high concentrations of water may be effectively extracted from gas mixtures and organic liquids using GO membranes [106].

3.6. Application of graphene and GO in water purification

Graphene and GO are being explored for various water purification applications, including membrane filtration, adsorption, and composite materials for water treatment.

3.6.1. Graphene in water purification

Graphene is utilized in membranes for water desalination and treatment, leveraging their ability to filter out pollutants. Graphene sheets with tiny holes that could be employed as materials for water filtration. The diameter of 1 nm, or a billionth of a meter, is sufficiently large for water molecules to flow through. On microporous substrates, Han et al. [107] developed ultrathin (about 22–53 nm thick) graphene nanofiltration membranes (uGNMs), which successfully filtered water. To evaluate the effectiveness of uGNMs for water treatment, a dead-end filter was employed. It was discovered that the organic dye retention in the uGNM pure water flux was both moderate (≈20–60%) and high (>99%). GO can also be used to improve current techniques for shale hydrocarbon and rare earth metal extraction. When different raw materials, including rare earth metals, are extracted, two naturally occurring radionuclides, uranium and radioisotopes, are brought to the surface of large amounts of water. This response has a serious problem. This water can be purified using GO. This phenomenon enhances the environment surrounding the deposit and effectively combats radionuclides and heavy metals. A graphene-based water filters for heavy metal removal is shown in Figure 3 [108].

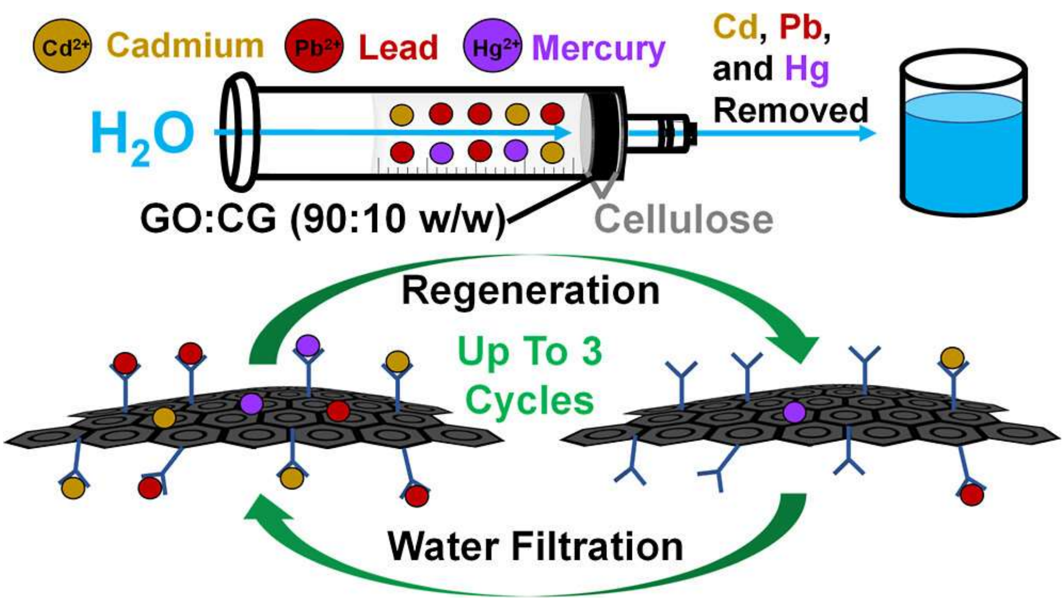

Figure 3. Graphene-based water filters for the removal of heavy metal (Reproduced from Ref. [108] with permission).

3.6.2. Graphene in alcohol distillation

Because of graphene's unique and fascinating physical properties, large water molecules can pass through it, but "He-molecules" cannot. It was discovered that graphene is an efficient ethanol distiller. The graphene membrane was used to test sealed vodka [109], with potential uses in water filtration, alcoholic beverage applications, fuel, and others.

3.6.3. Graphene in desalination

Graphene/GO/r-GO nanoparticles offer exceptional water purification effectiveness due to their distinct physicochemical characteristics, high selectivity, and water permeability. Graphene/GO/r-GO nanoparticles offer exceptional water purification effectiveness due to their distinct physicochemical characteristics, high selectivity, and water permeability. The potential of graphene membranes for water desalination is presented by Homaeigohar et al. [110].

3.6.4. GO in water purification (filters)

The phrase "water treatment" describes a group of mostly industrial processes that raise the standard of water for drinking, drinking, and industrial uses. It is the process of reducing or getting rid of existing water contamination. GO is an antibiotic that prolongs the life of water purification systems and lowers energy consumption by minimizing membrane biofouling. People worldwide use drinking water filters at home. Heavy metals can be successfully removed from drinking water by these filters; however, filters can quickly get saturated when heavy metals are present. Currently, this necessitates a complete filter replacement; filter manufacturers do not advise treating or regenerating (re-activating) the filter. A sustainable water filter made of graphene that can be renewed by treating it with vinegar (a mild acid) or hot water (80 °C). The filter has several favorable characteristics for the adsorption of heavy metals, such as conjugation, high surface area, and functional groups that contain oxygen. Compared to activated charcoal, this regenerable filtration system eliminates three to sixty-five times as much heavy metal (lead, cadmium, and mercury) from tap water. A straightforward regeneration procedure can be applied to the filter, enabling up to three cycles of reuse prior to metal breakthrough. This graphene-based water filter could be easily integrated into current at-home water filtering technologies, offering a more sustainable filter choice because it requires fewer filter replacements than present technologies. The expansion of the GO structure is responsible for water permeation over the membrane, making it appropriate for water purification utilizing a cation exchange membrane with solutions of KCl, HCl, $CaCl_2$, $MgCl_2$, and $BaCl_2$ [111,112]. In this case, the permeability is around 100 times greater than that of the best membrane on the market. GO may therefore be helpful in water filtration.

3.6.5. Graphene in the removal of pollutants from wastewater

The removal of contaminants, particularly pharmaceuticals, is a challenge for conventional wastewater treatment techniques. Adsorption, sophisticated oxidation techniques, and membrane filtering are a few of the techniques. GO’s large surface area and high adsorption capacity make it effective for water purification, particularly in removing pollutants like dyes and heavy metals. Because graphene, GO, and its composites exhibit adsorption, oxidation, and catalytic capabilities, they have been widely used for wastewater treatment. Natural pore volume, high conductivity, rich surface chemistry, and an extraordinarily wide aspect ratio are characteristics of graphene, GO, and its composites that make them ideal for the adsorption and catalysis of organic contaminants from wastewater. The polyaromatic, sheet-like, resonating π-system of graphene subsidiaries is important for π-π interactions, hydrogen bonding, and/or electrostatic interactions with organic pollutants, such as dyes, pharmaceutical waste, and industrial and agricultural effluents, whose base structure is composed of functional groups rich in oxygen and notably reactive unsaturated aromatic rings. Of the several techniques, adsorption is appealing due to its cost-effectiveness, environmental friendliness, and good pollution removal capabilities. According to Thakur et al. [113], advanced methods for treating water are provided by highlighting the applications of oxidation, catalysis, and adsorption in the removal of dangerous contaminants. By attracting and removing contaminants, the graphene-doped modified silica aerogels were found to be exceptionally successful at purifying water. This is due to the unique molecular structure of graphene, which boosts the aerogel’s accessible surface area. The material mimicked real-world settings in the studies by eliminating more than 85% of contaminants in a controlled environment and more than 76% in continuous flow conditions.

3.7. Application of graphene and GO in electronics

Graphene and GO have a wide range of applications in electronics, including flexible electronics. Graphene’s high conductivity and GO’s surface area make them valuable for various electronic device components.

3.7.1. Graphene in integrated circuits

An integrated circuit (IC), also referred to as a chip, is a small electrical device made up of multiple interconnected electronic components, such as resistors, capacitors, and transistors. Devices like laptops, smartphones, televisions; a few of the numerous electronic devices, have been greatly impacted by their capacity to facilitate device reduction and increased functionality. Field effect transistors could make use of graphene due to its high carrier mobility and low noise. Production of single sheets of graphene is challenging, and challenge increases significantly if the incorrect substrate is used. The tiniest transistor, with atomic thick and ten atomic broad, was made by Ponomarenko et al. [114]. Graphene transistors of the n- and p-type were developed by Wang et al. [115] p- and n-type graphene transistors combine to form functional graphene IC, a complementary inverter. Saeed et al. [116] designed an IC that enables the fabrication of fully integrated radio frequency (RF) and millimeter-wave frequency direct-conversion graphene receivers by tailoring the front-end architecture to exploit the cutting-edge performance of the wafer-scale CVD metal-insulator-graphene diodes.

3.7.2. Graphene transistors

Graphene-super-transistor technology can build computers up to a thousand times quicker than current silicon technology. For the development of many technologies, including financial markets, robots, block chain, and space simulations, efficient computer speed is an essential initial step. In contrast to other materials, graphene is a semimetal with a linear density of electronic states, linear energy dispersion, and a unique electronic structure. In the lower energy range, "dirac cones" are formed by valence and conduction bands. Dirac points are the sites where these cones intersect. Because of its strong electric field effect, which results in an electrostatically tunable carrier density and high carrier mobilities for both electrons and holes, graphene has garnered a lot of interest as a possible material for a high-speed field effect transistor (FET) in the future [117,118]. The most frequently studied graphene FET structure is the back-gated design, in which the graphene flake is attached to create source and drain electrodes and acts as a back-gate. A dielectric layer can be applied on top of such devices to transform them into top-gate arrangements. A single (top) gate can be used to fabricate several devices because graphene can be produced on SiC. The SiO_2 layer acts as a back-gate dielectric in a graphene MOS device, whilst the doped silicon substrate acts as the back-gate. Top-gated graphene metal-oxide-semiconductor field-effect transistors (MOSFETs), which are based on graphene grown on Ni/Cu metal [117] and epitaxial graphene, employ SiO_2, Al_2O_3, and HfO_2 as top-gate dielectrics. On flexible polymer substrates, Kim et al. [119] created graphene-FETs with excellent low-voltage performance. Britnell et al. [120] used graphene's single atomic layer and low density of states to produce a bipolar FET. These devices exhibit switching ratios of roughly ≈50 and ≈10,000 at room temperature, respectively. These devices may be used in large-scale integration and high-frequency operation.

3.7.3. Graphene as ballistic transistors

Room-temperature graphene has high mobility, ballistic transport is possible in nanodevices. *p-n-p* transistors allow Klein tunneling physics and the construction of devices that use the Fabry-Pérot cavity in the ballistic domain. Wilmart et al. [121] suggest a Klein tunneling transistor based on the geometrical optics of DFs. They considered the possibility of 100% internal reflection and tunable suppression of transistor transmission in a prismatic region enclosed by a triangle gate. Liang et al. [122] further investigated ballistic graphene nanoribbon FET performance predictions and found that the material acts like a high-mobility digital switch and may outperform silicon MOSFET.

3.7.4. Graphene in waterproof electronics

One of the most significant concerns is dropping electronic devices into water. To function electronics devices in damp or wet environments and avoid oxidizing or reacting with oxygen, it is imperative that materials that are resistant to moisture and water be utilized in their construction. Graphene offers a great solution to this problem instead of enclosing the device with finely positioned screws. Graphene is susceptible to humidity under these conditions, though, because of the water molecules in the surrounding air that are deposited onto its surface. The electrical resistance of graphene is altered by water molecules, which causes the sensor to provide an inaccurate result. The contact resistance of graphene when it bonds to the metal in electronic circuits is unaffected by moisture. Graphene has been used in silica substrates, gold metallization, computer simulations, and transmission line model test structures. By combining graphene with conventional electronics, one can take advantage of both the unique properties of graphene and the affordability of conventional integrated circuits. One way to combine the two technologies is to place graphene on top of finished electronics rather than metal on top of the graphene sheet. Because graphene flakes can be printed, sturdy, transparent, and conductive circuits for the device can be made. The graphene is bonded with anon-conductive glue and arranged in a certain manner to improve conductivity. As in other application areas, graphene offers a good answer to this problem [123].

3.7.5. Graphene in wearable electronics

One great technique is to use graphene-printed flexible batteries on fabric. By doing this, consumers can wear the battery and charge their smartphone or other gadget. If this idea is successful, an eco-friendly, intelligent e-textile with energy storage will be produced. Due to this ingenious concept, hauling heavy power banks or chargers around will become obsolete [124].

3.7.6. Graphene in flexible electronics

The 2D related crystals and hybrids, graphene offers advantages over conventional materials used in optoelectronic devices in terms of cost and performance. It also makes production methods more flexible. They can be used in a wide range of applications, including touchscreens and flexible displays, thanks to their versatility. Figure 4 illustrates the various flexible electronics uses of graphene and GOs [124].

Figure 4. Different flexible electronic applications of graphene and GO (Reproduced from Ref. [124] with permission).

3.7.7. Graphene as spintronics

Spintronics is the application of the spin degree of freedom of electrons to novel logic and information storage devices. For spintronic applications, graphene is a material of interest due to the discovery of room-temperature spin transport with long spin diffusion lengths of several micrometers. McCreary et al. [125] demonstrated that pure spin current is used to create magnetic moments in monolayer graphene due to lattice vacancies and hydrogen adsorbed atoms. The nonlocalized spin transport signal shows a clear hallmark of magnetic moment production when hydrogen adatoms are injected in a vacuum environment following the injection of a pure spin current into the graphene spin-valve devices. In spintronic functionality, it has been observed that graphene's spin-spin couplings are intriguing [125,126]. Swartz et al. [127] measured and studied the nonlocalized graphene tunneling spin valve of magnesium adsorbed atoms. When exposed to monolayer graphene, the charge transport behavior changes noticeably, although the spin relaxation time is little impacted. They found that the charge transport properties had a reduced mobility and momentum scattering time. In their investigation of spin relaxation in graphene spin valves, Han et al. [128] discovered a considerable difference in the behavior of monolayer and bilayer graphene. When it comes to single-layer graphene, the spin lifetime (τ_s) and momentum scattering time (τ_p) vary linearly, but when it comes to bilayer graphene, τ_p and τ_p show an inverse dependency. Graphene spintronics has advanced significantly in recent years. In the future, there will be many more opportunities. The source of spin relaxation in graphene is a major unsolved issue, and long spin lifetimes and spin diffusion lengths are essential for graphene-based spintronic devices. Moreover, the nature of magnetic interactions in graphene is poorly understood. Additionally, the graphene 2D materials should lead to the development of new devices and spin-dependent physical properties due to enhanced spin-orbit and exchange interactions.

3.7.8. Graphene in hard disk drives (HDDs) and memories

Numerous physical and chemical properties provided by graphene could improve existing memory technologies and open the door for the creation of future storage systems that are more cost-effective, flexible, and wearable. The employment of suitable recording technologies, such as heat-assisted magnetic recording (HAMR) and HAMR+ bit-patterned media, is expected to enable the development of 4–10 Tb/in^2 areal density HDDs [78] novel pathways for integrating these material structures into the current NVM device flows will be opened by the development of this novel apparatus. As selective growth is in its early stages, the transfer process is anticipated to be the most viable method for creating high-quality stacked films for some time to come.

3.7.9. Graphene in electronic tattoos and fitness tracking

Novel classes of wearable electronics, tattoo-like epidermal sensors are prized for their softness and thinness. Graphene electronic tattoos (GETs) provide better elasticity and moisture resistance than most, which rely on silicon membranes, thin metal films, or printable inks based on nanoparticles. They have a thickness of ~463 ± 30 nm and about 85% optical clarity, adhering to the skin like a second layer. These tattoos have uses in the medical and fitness tracking domains because they can measure heart rate, temperature, hydration, oxygen saturation, and UV exposure. A translucent, submicron-thick electronic tattoo for flexible, non-invasive multimodal biometric sensing was created by Ameri et al. [129]. The economical "wet transfer, dry patterning" technique is used to create this tattoo-on-tattoo paper, which lessens the chemical pollution associated with ground energy technologies (GETs). Without the need for adhesive, the GET can be applied straight from the tattoo paper to human flesh. It can tolerate skin deformation for a long time without cracking or peeling off, and it can adapt to the microscale texture of the skin. Electroencephalogram (EEG), electrocardiogram (ECG), electromyography (EMG), skin temperature, and skin moisture levels can all be measured with the GET. The GET-skin interface's impedance is almost as low as that of dry Ag/AgCl gel electrodes because of its remarkable conformability. As a result, the GET obtains an SNR that is comparable to gel electrodes and displays similar motion sensitivity. Like a tattoo, the GET is a certified wearable sensor for skin temperature and moisture that has been tested against the gold standard. Ameri et al. [129] claim that the GET has made it easier to employ two-dimensional materials in a variety of applications, such as biosensing electronic tattoos.

3.7.10. GO/r-GO in electronic devices

GO is a fundamental substance used in many electrical devices. One prominent example is the use of graphene in field-effect transistors (FETs) [130]. The r-GO-based FETs have been used in chemical [131–134] and biosensors [135]. Polymer solar cells [132], avidin [133], glucose [133], and hormonal catecholamine chemicals [134] can all be detected by these r-GO functionalized FETs acting as biosensors.

3.8. Application of graphene and GO in transparent conductors

Graphene and GO are promising materials for transparent conductive films (TCFs) due to their high electrical conductivity, optical transparency, and mechanical properties. These materials are being explored as replacements for conventional transparent conductive oxides like ITO in various applications, including touch screens, liquid crystal displays, and solar cells.

3.8.1. Graphene thin film as electrodes

In comparison to metals, graphene is a thin, elastic, and flexible substance with exceptional electrical and thermal conductivity. It is regarded as the "ideal" material for creating next- generation TC-electrodes, which are crucial for a variety of technologies, including touchscreens, smart windows, organic photovoltaic cells, solar cells, LEDs, and OLEDs, because it is stable and chemically inert. It also acts as an impermeable barrier. With a mobility of 0.1 $cm^2V^{-1}s^{-1}$ and an on-off ratio of 105, the organic thin-film transistors (OTFTs) built by Basu et al. [76] with graphene source-drain (S-D) electrodes outperform those with Au-based S-D electrodes. Additionally, Basu et al. [76] looked at the feasibility of using graphene.

3.8.2. Graphene in flexible screens

Applications such as flexible touch screens, displays, printable electronics, flexible transistors, and thin-film photovoltaic all depend on flexible transparent conductors (FTCs) [77]. Moreover, because of its two-dimensional structure, great transparency, exceptional electron mobility, chemical and thermal stability, affordability, and most importantly extreme flexibility, graphene has become a viable substitute for ITO in FTCs. High-temperature CVD of graphene onto a rigid substrate, followed by a transfer procedure, and solution processing of dispersed graphene or GO directly onto a flexible substrate are two well-known techniques for creating graphene-based FTCs.

3.8.3. Graphene in touchscreen

Due to its better strength and flexibility over materials like indium tin oxide, which are utilized in electronic products like laptops, smartphones, e-books, and cell phones, graphene, which is transparent and conductive, is a great choice for touchscreens. Since graphene has many benefits over ITO, including high transparency, low sheet resistance, and flexibility for plastic substrates, it can be used to create touch screen electrodes. Various commercial touch screen devices are available on the market. Transparent graphene film is expected to soon take the place of ITO film in touch screen electrodes. Different flexible screens electronic devices based on different sheet resistance are shown in Figure 5 [29]. By identifying an electrical short between the transparent conductive films on the top and bottom layers, resistive touch screens work. At a wavelength of 550 nm, they need transmittance of about 90% and sheet resistance of over 550 ohms per square. The fabrication of four-layer graphene on flexible PET-substrates produced an R_S = 30 Ω/square and almost 90% transparency at 550 nm wavelengths, according to a study [77]. Furthermore, because transparent graphene films may be doped to have a sheet resistance of <100 Ω/square, they can be used to build capacitive touch displays.

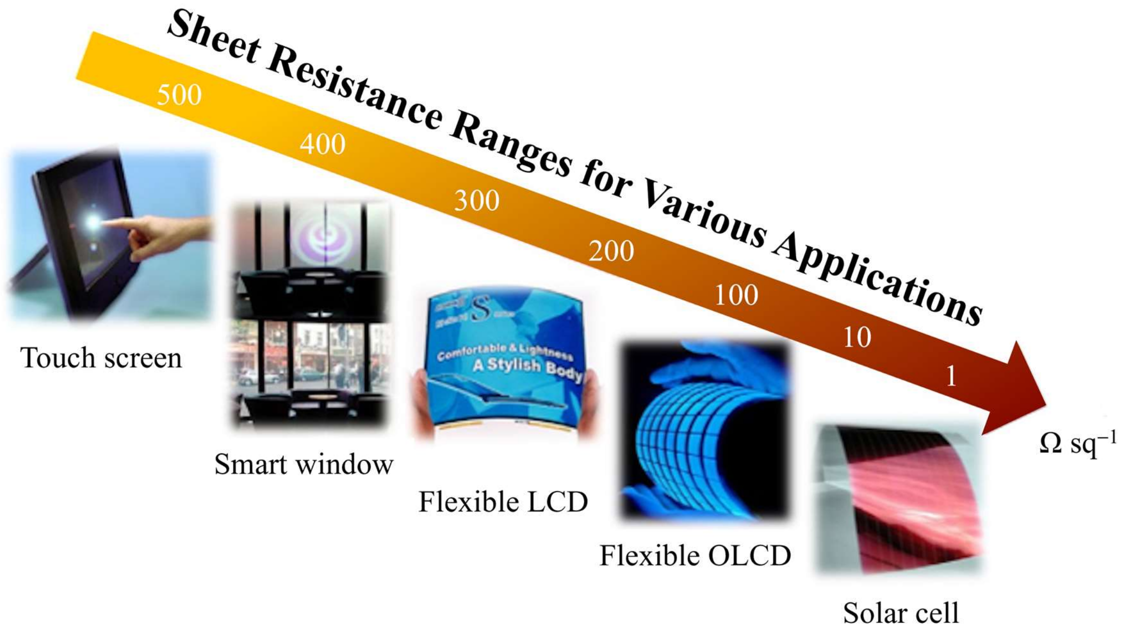

Figure 5. Graphene applications, corresponding resistance range required for each application (Reproduced from Ref. [29] with permission).

3.8.4. Graphene as a superconductor

The "twisted bilayer graphene" exhibits flat bands at zero Fermi energy. With a critical temperature of roughly 1.7 K, the material can be adjusted to zero-resistance states that could be used as a superconductive material after being electrostatically doped away from these equivalent insulating states [80]. There is no resistance for electrons to travel through two graphene layers. Twisted bilayer graphene is believed to have a superconducting phase when the relative twist angle between the layers creates a moiré pattern. A superconducting state manifests because of the moiré super-lattice flattening the electronic bands, which results in stronger electron-electron interactions. Twisting two graphene layers at the "magic angle" of 1.1° may accomplish this. Most of the superconductive materials show their properties at temperatures close to absolute zero. Even high temperature superconductive materials can operate at −140 °C in comparison to regular materials. In other words, it takes much energy to cool these superconductive materials. If graphene is used as a superconductive material, several application areas will undergo a significant change.

3.8.5. Graphene in elastic robots

By using flexible materials that can interact with living things, scientists are investigating soft robotics to close the gap between people and robots. The development of soft smart materials that can convert external energies like heat, light, or chemicals into mechanical energy for programmable morphing actuation could greatly progress untethered soft robotics. Wang et al. [79] used stacked graphene assembly/polyethylene (SGA/PE) bilayer films to create programmable untethered soft robots at a reasonable cost. Using the unique asymmetric elastic-plasticity of SGA under tension and compression, this technique incorporates thermally induced morphing systems as soft actuators and light-driven motors.

3.8.6. Graphene in a perovskite-graphene device for X-ray detection

An X-ray detection sensor known as a "perovskite-based graphene field effect transistor" (P-GFET) was developed by Snow et al. [136]. In the structure, spin-coated methylammonium lead iodide (MAPbI3) perovskite on top of a commercially available GFET-S20 chip served as the device design. Molybdenum targets were placed inside the apparatus and exposed to an X-ray tube field with beam characteristics ranging from 20 to 60 kVp (X-ray tube voltage) and 30–300 μA (X-ray tube current). Using an ion chamber and thermo-luminescent dosimeter to measure the dose in proportion to the X-ray tube voltage, current, and source-drain voltage enabled the determination of the apparatus's sensitivity. X-ray tube current, energy, and source-drain voltage all cause sensitivity to decrease exponentially, according to Snow et al. [136]. Furthermore, sensitivity and source-drain voltage are strongly positively correlated. The X-ray tube was also simulated in the work using GEANT4 and MCNP to determine the dosage rate and power incident on the device during irradiation. The simulation procedure was then used to determine the responsivity as a function of the X-ray tube voltage, current, and source-drain voltage.

3.9. Graphene and GO in thermal technology

Graphene and its oxidized form, GO, play a significant role in thermal technology due to their unique properties. Graphene's high thermal conductivity, excellent mechanical properties, and large surface area make it suitable for thermal management applications.

3.9.1. Graphene heat dispersion technology

The introduction of small, high-power electronic devices has increased the significance and urgency of heat dissipation in thermal management. Using a water-based epoxy polymer matrix, Cheng et al. [137] developed heat-dispersing coatings that were both environmentally friendly and very efficient at dissipating heat. The preparation of the heat dissipation covering involved the use of fillers such graphene flakes, multiwalled carbon nanotubes, and Al_2O_3. The graphene was dispersed in a water-based epoxy by including poly(dimethyl diallyl ammonium chloride) and sodium di-hexyl sulfosuccinate. These two surfactants were used as a dispersion to improve the dispersibility of the carbon nanomaterials in the water-based epoxy. The synergistic effect of the well-dispersed fillers improved heat dissipation efficiency. According to the results, a water-based epoxy and a carbon nanomaterial-based heat dissipation coating may significantly reduce the thermal equilibrium temperature, providing a wealth of opportunities for thermal management applications.

3.9.2. Graphene in photo-thermal therapy

The use of photo-thermal therapy (PTT)-based combination therapy, which combines hyperthermia with chemotherapy or radiation, is a successful way to enhance cancer treatment [138].

To successfully eliminate abnormal cells, PTT uses radiation to create heat in a specific body location. PTT's effectiveness is improved by GO, which has several uses. It primarily makes it possible to deliver PTT and chemotherapeutic medications to tumor cells at the same time, which increases the effectiveness of the combination treatment compared to either treatment alone. Furthermore, an r-GO nanocomposite can be used for cancer cell bioimaging during PTT. It has been shown that PTT for brain cancer has eliminated all cancerous cells while preserving healthy ones by functionalizing GO with biocompatible porphyrin.

3.10. Graphene and GO in food technology

Graphene and its oxidized form, GO, are being explored for their potential to enhance food packaging materials. They offer advantages like improved barrier properties against oxygen and water vapor, better mechanical strength, and even antimicrobial and antioxidant properties, which can help extend the shelf life of food and prevent spoilage.

3.10.1. Graphene in food packaging

Graphene is a good material for coatings because it prevents the transport of water and oxygen. When used in food or pharmaceutical packaging, graphene membranes may extend the freshness of foods and drugs. This program can drastically reduce the amount of food waste that people throw away every day, despite its seeming simplicity. To decrease moisture and water vapor oxygen permeability, Goh et al. [139] created a PLA-graphene/GO/r-GO composite thin film with sandwich architecture and improved processability. Because of this, it can be used as a protective encapsulation in food packaging films for items like edible oil and potato chips. 'Graphene-coated paper' can prevent oxygen diffusion, preserve food quality and extend shelf life. GO-based films can inhibit the growth of bacteria and other microorganisms, extending the shelf life of food. GO in polymer nano-composites can improve barrier properties and mechanical strength of biodegradable packaging materials.

3.10.2. Graphene in food security

In the modern world, lean meat powder and antibiotics are widely misused, harming the environment and putting public health at risk. By promptly inspecting the area for the presence of antibiotics or lean meat powder residues, these risks can be prevented. Food toxins and organic contaminants can be detected and extracted using graphene. Food packaging is connected to graphene-enhanced applications' antibacterial properties. Li et al. [140] used a laser-enabled flexible electrochemical sensor on his, her, their, etc. finger to detect the presence of ractopamine (RAC), clenbuterol (CLB), and chloramphenicol (CAP) in meat. To convey electrical impulses, flexible graphene electrodes were made and printed in a room using a CO_2 laser. A portable electrochemical analyzer was then attached to them. The electrochemical response of CAP, CLB, and RAC in phosphate buffered saline (PBS) at pH 7.0 was investigated by Li et al. [140], who found that the linear ranges were 10–250 μM and the corresponding limits of detection were ≈1.29–7.81 μM. The lowest detected levels of CAP, CLB, and RAC in pork samples were 10–30 μM, respectively. The minimum detection levels for CAP, CLB, and RAC in milk are 5–25 μM, respectively.

Sensors provide information that prevents drug pollutants from entering the food chain and enhance the usage of finger sensors for food security. The material is first carbonized, after which it transforms into graphene. This method can be applied to problems pertaining to food security and enables the creation of any design.

3.11. Graphene and GO in composites materials

Graphene and GO are frequently used in composite materials due to their unique properties, including high strength, flexibility, and conductivity.

3.11.1. Graphene as composite materials

It has been demonstrated that adding graphene-based carbon nanotubes to a polymer matrix can improve its mechanical, electrical, and thermal characteristics [141]. The stability of the polymer and engineered electrical and thermal conductivity-two crucial properties for applications in avionics, space exploration, and homeland security-are significantly impacted by the addition of uniformly distributed graphene sheets to polymer nanocomposites at incredibly low filler concentrations. Screen printing, spray coating, and spin coating are methods for coating and applying graphene inks [94]. Inkjet printing can be directly integrated with processing of electrical and optoelectronic devices [142]. Numerous applications in optical communications, chemical analysis, medical instruments, and surgery are expected for these devices.

3.11.2. GO/rGO composites and paper-like materials

Graphene/GO/r-GO blends with a variety of polymers to create paper-like nanocomposites that are utilized for a variety of purposes, such as ion conductors, nanofiltration membranes, and hydrogen storage [143].

3.11.3. Graphene in cement

One of graphene’s major potential uses is in building construction, where its strength and low weight make it an ideal material. It might take the place of steel, but there are additional considerations than strength and weight. Rapid crack propagation, which can result in catastrophic failure, is graphene’s primary problem. The composites compressive and tensile strengths can be increased by chemically functionalizing GO, which could make it an exceptional reinforcing material for building projects. The mechanical qualities of regular Portland cement paste can be enhanced by GO due to its high crack tortuosity, indicating that the two-dimensional GO sheet may act as a barrier to stop cracks from spreading. In the post-peak zone, the GO-cement composite’s stress-strain curve widens, resulting in a more progressive failure. By increasing the synthesis of calcium silicate hydrate, the GO also increases the surface area of the GO-cement composite. GO can therefore be used to create composite materials based on cement [144].

3.11.4. Graphene in shoes

Composite materials composed of graphene and polymers are being investigated and used in a wide range of applications. Often, the objective is to give the polymers electrical conductivity without appreciably increasing their weight. To increase their conductivity, two-dimensional carbon, like graphene, is added to polycarbonate (PC), polystyrene (PS), and PET. Furthermore, because graphene forms strong interfacial interactions with the polymer matrix, it is well known for enhancing mechanical qualities. In these situations, graphene is not utilized alone but in conjunction with other composite materials. It is said that shoe bottoms made of graphene can endure for hundreds of years. Lunchev et al. [145] created ethylene vinyl acetate (EVA) foams with varying weight percentages of graphene and cross-linking agents (0.1, 0.2, 0.5, and 1.0) and examined the mechanical characteristics of these composites. They discovered that industrial prototype soles with 0.1 and 0.2 phr of graphene were softer than soles composed solely of EVA, suggesting that running shoes can be more comfortable. Additionally, the graphene-based prototypes demonstrated 30% more axial stiffness than the reference footwear, which is advantageous for running propulsion. Furthermore, graphene is twice as pliable and more effective as a cushioning material, according to compression testing. Furthermore, compared to reference samples, the prototype exhibits a 40% increase in abrasion resistance with 0.2 parts per hundred resins (phr) of graphene. Graphene-made shoes will not only survive longer than conventional shoes, but they will also continue to look good for longer. This material may be useful in creating EVA/graphene composites for high-performance sports footwear, which needs characteristics like low weight, effective impact absorption with energy return, and excellent abrasion resistance, given its impact on composite mechanical properties. In a lab environment, Lunchev et al. [145] investigated how graphene affected the mechanical characteristics of EVA foams. The ideal concentration of graphene for industrial sports shoe prototyping was then established, and the real footwear's characteristics were assessed. Graphene improves performance in athletic shoes in several aspects, including elasticity, toughness, and mechanical resistance. Additionally, graphene is a pioneer in the more glutted equipment and lighter, more flexible materials.

3.11.5. Graphene in helmets

A helmet should be long-lasting, lightweight, comfortable, impact-resistant, and sturdy. Graphene is used in bulletproof vests because of its exceptional strength, flexibility, and light weight as well as its ability to withstand hits. The higher heat conductivity of a graphene-coated helmet enables quick heat dispersion, preventing heat damage to the internal materials and improving user comfort. Because of these characteristics, graphene is now used commercially in motorcycle helmets. The coating's main benefit is the improved strength it offers by dispersing the impact force over a larger surface area. The rider's comfort is further enhanced by graphene's superior heat conduction and dissipation capabilities. High outside temperatures do not affect helmet impact resistance because of the heat dissipation effect. Ali et al. [146] used a paraffin/nano graphene composite phase change material (PCM) to create a cooling system for these safety helmets. By absorbing and retaining heat, this PCM provides the user with comfortable cooling. By adding nanoparticles in different proportions, a PCM's thermal conductivity which is correlated with its capacity to absorb heat-can be improved. By keeping the temperature between 28 and 33 °C, the PCM in industrial helmets guarantees the user's thermal comfort.

3.11.6. Graphene in tires

Smarter tires and bicycle components are increasingly containing graphene. To increase the tire's useable life, the middle tread's graphene composition is designed to decrease rolling resistance and punctures. In addition to being notably lighter, stronger, and faster, tires with graphene infusion typically show improved speed and puncture resistance as well as reduced rolling resistance. They also offer more resistance, durability, and better grip in damp circumstances [147]. This substance helps prevent heat build-up and enhances Grand-Tour winning performance.

3.11.7. Graphene in rackets

It is possible to alter a racquet's weight distribution without altering its total weight by adding a sturdy, light material, such as premium graphene, to the racquet's core. Power and control are not compromised with graphene racquets. The resin-rich zones at the discontinuity of fiber tows in the racquet shaft, which joins the handle to the racquet head, were reinforced by Young et al. [148] using graphene-based nanoparticles (NPs). The racquet frame is mostly made up of high-strength carbon fibers embedded in an epoxy resin matrix. Graphene, more precisely graphite nanoplatelets, has been used to reinforce the discontinuity in the fiber tows, a possible weak point in the racquet. Most likely, the racquet contains these nanoparticles. The purpose of adding nanoplatelets is to improve the mechanical characteristics of the racquet's shaft's resin-rich regions. Additionally, the addition of graphene results in improved energy and weight distribution, as well as faster and more stable service. These sports products streamlined, lightweight designs are meant to improve durability, boost comfort, reduce the risk of injury, and provide consumers a competitive edge.

3.11.8. Graphene and silk

Hybrid composites of silk fibroin and graphene/GO/r-GO offer enhanced biocompatibility, electrical conductivity, and mechanical qualities. Applications for these nanocomposite materials include coatings, films, and membranes [149]. They can drastically lower the risk of catastrophic failure resulting from insufficient load transmission between components and are more effective at transferring loads than standard composites. Silkworms were given turmeric leaves sprayed with a 0.2% graphene solution to improve their silkworm behaviors. The results were encouraging because commercial silkworms fed the leaves treated with graphene generated 10 times as much silk as regular silkworms.

3.11.9. Graphene in clothes

One notable invention that may have a big impact on wearable technology is graphene. Graphene-infused fabric is adaptable and perfect for making a variety of winter clothing items, including gloves, battery-heated jackets, coats, shirts, jeans, and socks. Clothing with UV protection, heat retention, antibacterial, and antistatic qualities can be made by weaving graphene threads into textiles. These cutting-edge textiles can be used to create outdoor sportswear, furniture covers that inhibit bacterial growth, and even children's sleepwear that fights soil bacteria. Although graphene fabric absorbs heat in hotter areas, it is a great option for any season due to its ability to disperse and hold body heat evenly. This is how the graphene fabric naturally modifies its temperature to match the temperature of our bodies. To facilitate long-wavelength infrared communication, Ergoktas et al. [150] created an active device that can be attached straight to a T-shirt and controls the body's heat radiation.

3.11.10. Wearable graphene-garment sensor (e-Textiles)

Through a simple pad-dry process, graphene-based clothing can be used in wearable sensors by chemically decreasing GO/r-GO [151]. This material could be utilized in graphene sensor clothing, which uses the energy stored in graphene textile supercapacitors to serve as both flexible heating elements and sensors at the same time.

3.12. Application of graphene and GO in the defense sector

Graphene and GO have promising applications in the defense sector, primarily due to their unique properties like high strength, light weight, and thermal/electrical conductivity. These materials are being explored for use in ballistic protection, lightweight armor, military helmets, and various electronic components.

3.12.1. Graphene in military protective equipment

Different materials are used to create personal protection equipment depending on the end-user's requirements and any dangers. Fabrics may now successfully handle problems with conductivity, UV resistance, mechanical strength, and antibacterial activity because to graphene's exceptional qualities. The application of graphene composites in vehicle armor, vests, and helmets can improve safety for military troops by increasing their resistance to bullets and shrapnel [152]. Potential uses for graphene have been recognized by the armaments industry, including materials for stealth technologies aimed at protection and shielding. Additionally, graphene might be utilized to create a variety of protective gear, including helmets and vests that are bulletproof for military and law enforcement personnel.

3.12.2. Graphene in ballistics

Graphene and GO are being investigated for use in lightweight and high-strength ballistic protection materials, potentially reducing the weight and increasing the effectiveness of body armor. High strength-to-weight ratio of graphene and GO makes them ideal for developing lighter yet more durable armor systems for military vehicles and personnel. Bullet proof vests, protective gear, helmets, and weapons are frequently constructed from an organic fiber known as "Kevlar". Graphene-Kevlar composites, on the other hand, absorb more heat, protecting the fibers and providing more comfort. As a result, materials like graphene/GO/r-GO are better than Kevlar for ballistic applications [153]. Graphene helmets can be lighter and more comfortable for soldiers while providing excellent impact resistance.

3.12.3. Graphene in aviation

Graphene-based electric ice prevention systems save energy without sacrificing safety by preventing ice build-up on vital aircraft components. Researchers have created a plane with graphene integrated into the carbon-fiber wing coverings. The aircraft's wings can be covered in a single layer thanks to this sophisticated composite's adequate weight. The potential application of graphene in aviation lightning protection systems is suggested by its high electrical conductivity and low weight, which make it perfect for energy transmission at the contact site. As a result, the conventionally employed copper mesh for this purpose is starting to give way to graphene composites with conductive polymers. Easy-to-install lightning protection devices are standard on modern airplanes. These technologies provide enhanced impact resistance in addition to lowering fuel usage and environmental expenses [154].

3.12.4. Graphene in thermal and infrared vision

Graphene lenses are a major technological advancement that enables thermal and infrared vision. Graphene enables the development of incredibly thin gadgets with integrated cameras, providing users with the capacity to see infrared and thermal images. According to Rogalski et al. [155], graphene-based terahertz and infrared detectors are less effective than those that are already available on the global market. The sluggish response time of hybrid photodetectors counteracts their great sensitivity. The best single graphene detectors at room temperature, however, are terahertz detectors that use plasma rectification in FET. With a focus on the main trends that will soon shape array evolution, future developments in focal-plane arrays are being contemplated. Pixel diameters are predicted to drop to about 5 µm, and pixel counts are anticipated to surpass 108 for cooled/uncooled long-wavelength infrared arrays.

3.12.5. Electronic components and sensors in the defense sector

Graphene and GO can be used in the development of high-speed, energy-efficient electronic devices for use in military communications, radar systems, and other critical equipment. Graphene's ability to detect a wide range of chemicals and its high sensitivity make it suitable for developing advanced sensors for detecting threats like explosives or toxic gases.

3.13. Application of graphene and GO in lubricant and coating technology

Graphene and GO offer significant potential in lubricant and coating technologies due to their unique properties like high strength, low friction, and excellent thermal conductivity. They can be used as lubricant additives to reduce friction and wear, and as components in coatings for enhanced durability and protection.

3.13.1. Graphene in machinery lubricants

Graphene can be combined with other solid lubricants or surfactants to further enhance lubrication performance and stability. Graphene's also an excellent thermal conductivity makes it an attractive option for improving the thermal management of lubricants, particularly in high-temperature applications. Graphene/GO/r-GO and related nanocomposites could be used in lubricating applications and tribology to lessen machine wear and tear [156]. Friction is a serious issue since it has a substantial impact on the robustness, durability, and effectiveness of industrial machinery. Both liquid and solid lubricants are used to lessen these effects. With its distinct mechanical, chemical, and physical characteristics, graphene presents a viable option for a liquid-based lubricant additive. It shields surfaces from wear and lowers friction. Graphene also helps liquid lubricants dissipate heat, which improves wear performance. Graphene is becoming a more versatile lubricant that works well in both liquid and solid forms because of its better wear and friction characteristics when compared to conventional materials. Graphene is a great lubricant material because of its high chemical stability and smooth, densely packed surface. The creation of graphene-based nanocomposites for lubrication and tribology applications has been investigated by Sun et al. [156]. Regardless of whether the lubricant is liquid or solid, the boundary tribo-film occupies the finite domain of frictional contacts, and the microscopic actions of the boundary tribo-film determine the macroscopic tribological features of these interfaces. Van der Waals forces primarily adsorb the nanosheets at the interfaces because graphene is chemically inert, producing a physical adsorption tribo-film. This tribo-film is not strong enough to form a long-lasting covalent connection with the atoms at the frictional interface, though. Therefore, one of the most important areas of research is coming up with efficient ways to increase graphene's covalent adsorption capability at the frictional contact to create a long-lasting border tribo-film. Using covalent or non-covalent methods to adorn graphene nanosheet surfaces with nanoparticles and other 2D materials is a practical way to deal with this problem and enhance the interfacial lubrication performance [156]. Graphene as a dry lubricant used in highly loaded rolling bearings because graphene as a dry lubricant and as a grease additive under rolling contact conditions reduces friction significantly [157,158]. GO can be used in water-based lubricants, improving their efficacy due to its water dispersibility and mechanical properties.

3.13.2. Graphene in corrosion protection for glass

Graphene coatings can provide superior chemical, moisture, corrosion, and UV resistance. A physical barrier network made of SiO_2, clay, boron nitride, and graphene can effectively shield glass from corrosion by preventing corrosive substances from entering and spreading. Glass can be coated with graphene. High pH or high humidity can cause glass to deteriorate even if it has a great barrier to corrosion. Additionally, glass's durability is crucial in sectors like optics and medicines. It offers defense against a range of issues, such as corrosion, oxidation, and electromagnetic radiation. With its exceptional chemical inertness and excellent transparency, graphene is a promising option for protecting glass. According to Hu et al. [159], graphene is impermeable because to its tightly packed carbon atom network, which stops corrosion in materials like glass and maintains the chemical characteristics of the material that is shielded. According to Wang et al. [160], graphene coatings act as barrier layers, preventing silicate glass from corroding due to water.

3.13.3. Graphene in radiation shielding

Graphene creates a continuous network across the surface of the coating to provide homogenous layers that effectively block radiation. It can be used to create coatings that provide electromagnetic radiation protection because of its electrical conduction and thermal conductivity qualities. The efficiency of different materials as sun shields varies depending on several parameters. Despite its remarkable shielding capabilities in multi-layered structures, such as graphene slabs, graphene remains a weak radiation absorber. When compared to alternative shielding materials, graphene is notable for being lightweight and extremely effective. Hashemi et al. [161] investigated how the GO/epoxy composite adorned with lead oxide improves the shielding against X-ray radiation.

3.13.4. Graphene for anti-corrosion oil and gas pipes

The outer layers of undersea pipelines that carry gas or oil can occasionally be penetrated by water and CO_2, which might eventually cause corrosion. These pipes are expensive to repair, and if they burst from corrosion, the contents could be dangerous to marine life. Effective defenses against this kind of corrosion are provided by graphene-based materials such as composites, multilayer structures, and thin films. To replicate the temperature and pressure that pipes experience underwater, researchers have created a covering using graphene nanoplatelets. As a result, the permeability of CO_2 and other corrosive chemicals was significantly reduced by 90%. Zhang et al.'s study [162] highlights the material's structural characteristics while examining the function and mechanism of graphene in anti-corrosion coatings.

3.13.5. Graphene in insulation

When bi-layer graphene is placed at a particular "magic angle", it can act as a superconductor or an insulator. In cars, ships, and airplanes, most metal components are susceptible to rust. When added to paint, graphene can be a great insulator for surfaces that are not prone to corrosion. To examine the possible application of graphene-based multi-layer fabric heating components in protective apparel, Kim et al. [163] conducted electrical heating tests to examine the thermal insulation characteristics of these elements.

3.13.6. Graphene in automotives

This potential use of graphene in automotive coatings extends beyond the vehicle's exterior to any area where a coating is applied to enhance corrosion prevention, boost lubrication, reduce friction, shield underlying components or devices, and protect a variety of other applications, such as drivetrains and engine parts [157]. Graphene is perfect for making impact-resistant automobiles because of its exceptional strength, flexibility, and hardness. Accident-resistant vehicles may be created, which could result in fewer people dying on the roads. Graphene-based vehicles are expected to become lighter and cheaper in the next ten years.

3.13.7. Graphene in paints

Every painter is aware that moisture damages paint. Graphen-stone creates graphene paint solutions that improve light reflection, prevent corrosion in cellars and barrels, and absorb 120 g of CO_2 per square meter. Using a modified Hummer's approach, Sousa et al. [164] studied a wall latex paint that included GO and was utilized as a building paint. Coatings with and without GO added were examined, and it was shown that GO enhanced $CaCO_3$ crystallization as well as compound dispersion and mixing throughout the coating manufacturing process. Wall latex paints with GO outperformed those without in tests of wet and dry paint hiding power when applied to buildings, fulfilling all minimum standards. Additionally, paint containing 1.0% GO showed a larger contact angle, indicating better hydrophobicity and cleaning qualities, according to Sousa et al. [164]. It is advised in the areas of paint rheology, color alteration, aging, water vapor permeability, stain resistance, surfactant leaching, and adhesion to gain a more thorough understanding of the recently produced material [164].

3.13.8. Conductive adhesive paste

Conductive adhesive pastes are specialized adhesives designed to transmit heat or electricity. A variety of adhesives designed to meet conductivity requirements are among them. Electrode-based adhesives, conductive silicone, nickel, copper, carbon, and silver conductive pastes are among the several types of conductive adhesive pastes. Excellent chemical stability, strong adhesion, and electrical conductivity are characteristics of conductive carbon paste, a high-performance substance. It is a versatile element that can be used as a dependable electrode in electrochemistry, an essential part of sensors, or a dependable element in electrical systems. Demand for it is rising quickly, particularly in the sector that makes solar panels. Conductive adhesive comes in a variety of forms, including carbon gripper paste, carbon assembly paste, carbon montage paste, carbon seat post paste, and thermoplastic paste. Particularly in solar and renewable energy systems, graphene paste is used as an excitation material [165]. It has a wide range of applications because of its excellent conductivity, flexible structure, broad compatibility, and functionality in energy conversion and storage systems [165].

3.13.9. GO/rGO in coating technology

GO can be used to create transparent and conductive coatings for various applications, including digital displays and solar panels. Use of GO/r-GO coating process could result in high-performance coatings that increase a water resistance, corrosion resistance, and longevity. Gases, liquids, and heavy compounds cannot pass through multilayer GO sheets, which are tiny capillaries that are more than 100 manometers thick. This graphene "paint" can be used to make corrosive acid storage tanks by applying it to copper plates or glasses. Medical packaging may use graphene-coated plastic films to increase shelf life [166]. It is noted that the thin diamond-like carbon layers are also very much useful in the coatings of different tools.

3.14. Application of graphene and GO in biological and bio-medical application

Graphene and its derivative, GO, are used in biological and biomedical fields due to their unique properties. These applications include drug and gene delivery, biosensing, tissue engineering, phototherapy, and antibacterial applications.

3.14.1. Graphene in crop protection

Graphene is a unique and practical nanomaterial that enhances plant nutrient uptake, increases soil nutrient component absorption, and reduces chemical fertilizer pollution by improving insufficient soil nutrient conditions. Graphene is a great option for sensors that assess whether a chemical is environmentally hazardous or not. These sensors have applications in the food industry, especially in crop protection. Farmers can use graphene sensors to monitor and detect harmful and toxic chemicals to crops, as well as determine the ideal growing areas for crops based on factors like moisture content, air quality, and plant “thirst”. Since pesticides are seen to be an efficient way to control and prevent major agricultural pests, they are frequently used to boost agricultural output. The public is more concerned about the toxicity, stability against natural decomposition, and environmental permanence of this. Pesticides are usually used in significantly larger amounts than are required to compensate for the loss and ensure that the effect lasts long enough. A growing number of negative effects on humans and the environment are unavoidably brought on by the extensive and frequent use of synthetic pesticides. These effects include pesticide residues, insect population recovery, the widespread development of pest resistance, and some unfavorable effects on creatures that are not the intended targets. To overcome these problems, GO is mixed with the insecticide chlorpyrifos and the acaricide beta-cyfluthrin. The results indicated that the GO could boost the efficiency of three distinct types of insecticides. In tests against T. truncatus and T. urticate, respectively, GO-cyfluthrin (Cyf), GO-pyrethrins (Pyr), and GO-chlorpyrifos (Chl) mixtures have shown contact toxicity that was 1.77-, 1.56-, and 1.55-fold higher than that of insecticides. Wang et al. [167] demonstrated the adsorption of pesticides on the surface of GO. It can work in concert to serve as a pesticide carrier, enabling pesticides to be absorbed on mite surfaces and increasing their efficacy and usage efficiency. Such GO-based nanoscale pesticide delivery technology may be widely used in the future for plant protection. Synthesizing and dispersing graphene in lubricants can be challenging, and further research is needed to optimize the process and fully understand the lubrication mechanisms.

3.14.2. Graphene in microbial fuel cells

Microbial fuel cells (MFCs) are made to create electrical energy from electrons generated by bacterially catalyzed metabolic reactions. MFCs are bio-electrochemical systems that use anaerobic reactions catalyzed by microorganisms to transform chemical energy into electrical energy. The type of proton exchange membrane and electrode materials employed in MFCs have a significant effect on the outcomes of numerous applications, such as wastewater treatment, bioremediation of hazardous chemicals, biosensor manufacturing, and the production of bioelectricity. Additionally, MFCs are operated at ideal parameters, such as thermophilic temperatures and neutral pH, to yield results that are more significant for the desired application [168]. Graphene-modified stainless-steel mesh, graphene and carbon-cloth, graphene and polyaniline (PANI) nano-fiber composites, and crumpled graphene electrodes have all been shown to function as MFCs [168,169].

3.14.3. Graphene in enzymatic biofuel cells

Like all fuel cells, enzymatic biofuel cells (EBFCs) use the same basic principles to transform chemical energy into electrical power. High performance EBFCs are anticipated [126] due to graphene’s exceptional conductivity, ballistic electron mobilities, and other outstanding characteristics. Graphene-based enzymatic biofuel cells have been produced by Tang et al. [170], who also describe the critical function of grapheme-based electrodes in bio- electrochemistry.

3.14.4. Graphene in contrast agents for magnetic resonance imaging (MRI)

Graphene and its derivatives serve as platforms or nanocarriers for magnetic nanoparticles because of their large specific surface area. This connection improves stability, stops particles from aggregating excessively, and boosts magnetic resonance efficiency considerably. The non-toxicity of graphene and its derivatives makes them highly promising for use as MRI biomarkers. All materials are affected by magnetic fields, including the tissues of animals. A powerful magnetic field in an MRI scanner aligns the body's atoms with the magnetic field. The instrument determines how long it takes for atoms in various body sections to realign after being disturbed by a radiofrequency pulse. The scanner creates detailed photographs of the internal architecture of the body using this alignment time. MRI contrast agents reduce the time it takes for tissues to realign and improve the resolution of these scans. Most contrast agents that are sold commercially are derived from potentially hazardous metals like gadolinium, manganese, or iron. In comparison to traditional contrast agents, graphene-based quantum dots which are made entirely of carbon, hydrogen, oxygen, and fluorine offer several advantages and have demonstrated no general toxicity. As a result, graphene has the potential to be used as an MRI contrast agent [171].

3.14.5. Graphene in diabetes monitoring

Graphene and GO/r-GO are perfect materials for micro- and microelectronic applications because of their excellent conductivity, flexibility, optical transparency, and carrier mobility. Graphene/GO/r-GO doped gold may improve the electrochemical activity that could be used in sweat-based diabetes monitoring and feedback therapy [172]. For electrical impulses to flow through, the device's expandable features provide a reliable and efficient electrochemical interface. This gadget can release metformin using thermal actuation, which decreases diabetics' blood glucose levels. They have developed a glucose test that differs from the currently used finger prick procedures. In addition to having a graphene sensor, this patch can work on a small area with at least one hair follicle. To detect glucose, it takes it out of the fluid that exists between cells. This should increase the accuracy of results and do away with the uncomfortable blood sugar monitoring methods.

3.14.6. Graphene in dialysis

Graphene is used to filter trash, poisons, and drugs from blood and is used in the food, pharmaceutical, and energy sectors. Since the new graphene membrane is less than one nanometer thick, it may speed up the dialysis process. The dialysis membranes are thick and slow. Patients require substantially less time for dialysis because graphene, which is 20 times thinner than conventional membranes, enables much faster diffusion. A nanoporous membrane that is atomically thin and appropriate for desalination and dialysis was created by Kidambi et al. [173]. To do this, graphene was chemically vapor-deposited onto supports etched with polycarbonate, the pores were sealed to stop leakage, and particular pores were formed. These nanoporous atomically thin membranes' size-selectivity and rapid diffusion have the potential to transform a variety of processes, including drug purification, reactant elimination, biochemical analysis, therapeutic treatments, medical diagnostics, and nano-bio separations.

3.14.7. Graphene in bone and teeth implantations

A material called hydroxyapatite is utilized in artificial bone substitutes to promote the regeneration of dental tissues and bones. Graphene nanoparticles are quickly taking the lead as the preferred nanostructure for contemporary biomedical applications because of their special qualities and possible benefits. Graphene nanoparticles have shown promise for use in dental implants. Compared to hydroxyapatite alone, the composite's strength, flexibility, and resistance to corrosion are improved, as are its mechanical and osteogenic qualities when mixed with chitosan. Because graphene has a higher surface area- to-volume ratio, it can interact with biological tissues more successfully. In addition, graphene's exceptional mechanical qualities and high conductivity could make dental implants stronger and more resilient. Research on dental implants based on graphene nanoparticles is an exciting and novel area. More research is necessary to fully understand the potential benefits and risks of using these particles, although preliminary data suggests that they may be helpful in improving the success rates and long-term outcomes of dental implant treatments. A summary of the current state of the art in dental implant technology may be found in Mobarak et al.'s examination of graphene nanoparticle research [174]. Dental implants that incorporate graphene nanoparticles may enhance interdisciplinary cooperation, identify attractive research areas, and progress clinical practice. With this information, dentists can make an informed decision on whether to apply zirconium nanoparticles while treating dental implants. Potential development possibilities and the use of graphene nanoparticles in dental implants are now being investigated. This could direct future studies and result in dental implant instruments and processes that are more effective. Furthermore, a wider range of plant species may be used in the future to quickly and environmentally create metal oxide nanoparticles.

3.14.8. Graphene in tissue engineering and cell therapy

Graphene is a useful tool in tissue engineering and regenerative medicine because of its interactions with many biomolecules, including proteins, peptides, enzymes, and DNA. Because of its special qualities, which include high strength, flexibility, appropriate softness, electrical conductivity, antibacterial qualities, and the capacity to cross the blood-brain barrier, it is used in nerve tissue engineering. The potential for alterations that increase graphene's suitability and adaptability to cell cultures and tissues, both in vitro and in vivo, adds to its versatility [175]. Graphene also makes it easier to create tissues and organs for re-transplantation using the patient's own cells, which could eliminate transplant rejection, the negative effects of immunosuppressive medications, and the need to find an organ donor who is compatible. Applications for graphene go beyond the treatment of bone tissue. Human osteoblasts and mesenchymal stem cells have been shown to be compatible with specific graphene forms, which mimic the natural conditions of the cells. Without sacrificing cell viability, this compatibility has resulted in improved cell growth, proliferation, and differentiation. Stem cells are particularly important in tissue engineering, which greatly improves the quality of life for those with neurological or neurodegenerative diseases therapy [176].

3.14.9. Graphene for the brain

After ischemic heart disease, stroke is the second most common cause of mortality. The leading causes of morbidity, mortality, and disability worldwide are neurological conditions and brain diseases, such as multiple sclerosis, Alzheimer's, Parkinson's, Huntington's, motor neuron disease, stroke, traumatic brain injury, and brain cancer. One clinical objective in the treatment of neurological disorders like Parkinson's and Alzheimer's diseases is to penetrate the blood-brain barrier (BBB), which prevents several therapeutic approaches for drug delivery to the central nervous system [177]. Tightly woven endothelial cells make up most of the BBB, a highly selective cellular barrier. By acting as a gatekeeper, it keeps blood-borne infections out of the central nervous system. Although the complete complexity of the brain is yet unknown, research into tailored drug delivery strategies to penetrate the blood-brain barrier has been conducted in the last ten years. Many of these mysteries could be solved using graphene-based technologies to capture the electrical activity of the brain. With their remarkable qualities-such as high electron mobility, simplicity of synthesis and functionalization, and control over size, shape, and drug release profiles, graphene nanostructures have demonstrated a great deal of promise in terms of crossing the blood-brain barrier. Graphene is being developed as a minimally invasive treatment for neurological illnesses as well as a diagnostic tool for sick areas. Innovative graphene-based delivery systems have advanced quickly, enabling a new device that does not interfere with brain function to detect frequencies that are higher than those of previous technologies. Researchers can better understand the causes of epileptic seizures and how the brain works thanks to this technology. Understanding the workings of the brain may also result in the development of novel brain-computer interfaces with a wide range of uses. Additionally, graphene and its derivatives could be used as brain electrode materials.

3.14.10. Graphene in human immunodeficiency virus (HIV) diagnosis

The current state of HIV diagnosis technology has several shortcomings. Methods can identify viruses about a month after infection, but they are more expensive and take longer to perform than antibody detection. Using a polyaniline/graphene (PAN/GN) nanocomposite, an HIV biosensor was created. With a lower detection limit of 1.0×10^{-16} M, this sensor has demonstrated successful discrimination against non-complementary or sequence mismatches. The cutting edge of nanotechnology is represented by graphene or silicon biosensors embedded with gold nanoparticles. The latest generation of nanomaterials, GQDs have enormous promise for medication delivery and targeted HIV suppression. Iannazzo et al. [178] evaluated the antiviral capabilities of graphene-based materials using water-soluble GQDs produced from multiwalled carbon nanotubes (MWCNT) by prolonged acidic oxidation and exfoliation. The anti-HIV effectiveness of these GQDs was contrasted with that of reverse transcriptase inhibitors (RTIs) that were connected to the same nanomaterials. Iannazzo et al. [133] investigated using different non-nucleoside reverse transcriptase inhibitors (NNRTIs). The reverse transcriptase inhibitors (RTI)-conjugated compound GQD-CHI499 was found by Iannazzo et al. [133] to be a promising treatment candidate for HIV, with an IC50 (50% inhibitory concentrations *in vitro*) of 0.09 μg/mL and an EC50 (50% effective concentrations in vitro) value in cells of 0.066 μg/mL. Furthermore, for the drug-conjugated samples GQD-CHI499 and GQD-CDF119, the point of action within the HIV replication cycle was examined using a time of addition (TOA) technique. The results showed that conjugates' modes of action were comparable to those of NNRTI medications.

3.14.11. Graphene in biosensors

Graphene and GO/r-GO could be used to create biosensors that show extremely sensitive detection of a variety of atoms, ATP, dopamine, oligonucleotides, thrombin, and DNA. Several medical companies have brought graphene-based medical sensors to the market. Extensive research into graphene-based biosensors has been prompted by graphene's enormous specific area and important electrical, thermal, and biocompatibility features. By covalently connecting graphene sheets to glucose-oxidase (GO), a biosensor consisting of poly-pyrrole-graphene-glucose oxidase was created. The resulting electrode is used to monitor glucose. To detect dopamine in serum and urine with excellent sensitivity and selectivity, Liu et al. [179] created a dopamine biosensor based on a phenyl ethynyl ferrocene/graphene nanocomposite. Using an electrode modified with graphene/polyethyleneimine-functionalized composites, Shan et al. [180] presented the first graphene-based glucose biosensor. It demonstrated great stability and a glucose response range of 2 to 14 mM (R = 0.994). Furthermore, a graphene/AuNPs/chitosan composite film biosensor with notable electrocatalytic activity for H_2O_2 and O_2 was reported by Shan et al. [180]. Additionally, a thionine-graphene nanocomposite was developed by Zhu et al. [181] for electrochemical DNA biosensing. It has a remarkably low detection limit of 1.26×10^{-13} M and good selectivity throughout a range of 1.0×10^{-12} to 1.0×10^{-7} M. The performance of graphene composite film-based electrochemical sensors is improved by the complementary actions of graphene nanosheets and Nafion. These sensors reduced interference effects and improved sensitivity in detecting Pb^{2+} and Cd^{2+}.

3.14.12. GO/r-GO in biosensors

Graphene and GO can be used as biosensors to detect various biomolecules like DNA, proteins, and viruses. They can be used in optical, mechanical, electrical, and electrochemical biosensors. Graphene-based biosensors are used for monitoring human health, analyzing food, and sensing environmental pollutants. In addition, fluorescent GO/r-GO materials are used in early disease detection, cancer treatment, and the identification of physiologically relevant molecules. GO has been successfully used in fluorescent-based biosensors for the detection of proteins and DNA, which may enhance HIV diagnosis. GO has been used as a fluorescence quenching material in biosensors that utilize the fluorescence resonance energy transfer (FRET) effect. Wang et al. [182] used the FRET effect to detect adenosine triphosphate (ATP) at concentrations as low as 10 μM using a fluorescein-labeled ATP aptamer. Lu et al. [183] used single-stranded DNA (ssDNA) with a fluorescence tag and found that the ssDNA connected non-covalently to GO, quenching the fluorescence of the tag. After removing the tagged DNA from the GO surface, a complementary ssDNA was added to restore the fluorescence. Song et al. [184] used folic acid functionalized with GO to detect human breast and cervical cancer cells.

3.14.13. Graphene in bactericides

Because of the overuse of antibiotics and a lack of therapeutic research, multi-drug-resistant bacteria are becoming a global health concern. Researchers are interested in carbon-based graphene and GO because of its antibacterial qualities, although some contend that these substances might potentially encourage the growth of germs. Because it damages the cell membranes of bacteria, viruses, and fungus, graphene is thought to be an efficient antibacterial agent. This prevents the growth of various pathogens within its layers. GO and r-GOs are the graphene derivatives with the strongest antibacterial properties. GO can be combined with silver nanoparticles to further improve its antibacterial properties. Both gram-positive and gram-negative bacteria are susceptible to GO's bactericidal action. The duration and concentration of GO against bacterial strains affect its bactericidal effectiveness. The effects of GO and r-GO on gram-positive *Staphylococcus aureus* and gram-negative *Pseudomonas aeruginosa* were investigated by Sengupta et al. [185]. They found that r-GO had suppression rates of 67.7% and 93.3%, while GO reduced the development of S. aureus and P. aeruginosa cells by 93.7% and 48.6%, respectively. GO causes chemical damage to the cell membrane, r-GO cause's mechanical stress that punctures the membrane. The form and type of bacteria largely dictate the bactericidal effectiveness of nanoparticles. According to Prasad et al. [186], reduced r-GO's antibacterial qualities are improved by the addition of silver nanoparticles (nAg). It was investigated the rGO-nAg nanocomposite's antibacterial properties against several drug-resistant human infections, such as *Proteus mirabilis*, gram-negative *Escherichia coli*, and gram-positive *Staphylococcus aureus* (a gram-positive spherically shaped bacterium). They discovered that the rGO-nAg nanocomposite was substantially more efficient against all three bacteria than either rGO or nAg alone at a concentration of 100 μg/mL. When compared to the nanocomposite, the antibiotic nitrofurantoin was more effective against *E. coli* but less effective against *P. mirabilis* and *S. aureus*. Importantly, a substantially quicker inhibition was obtained when rGO-nAg nanocomposite was used in place of nitrofurantoin. This is explained by the interaction between oxidative stress and contact killing mediated by rGO-nAg. This study opens the door for the creation of better antibiotics and other graphene-based biological applications while offering fresh insights into the antibacterial qualities of the rGO-nAg nanocomposite.

3.14.14. Graphene in birth control

The technique of contraception is being revolutionized by the creation of an ultra-thin condom composed of graphene and latex. Graphene condoms are composed of an exceptionally thin yet robust layer of crystalline carbon and are intended to be thinner than existing latex alternatives while improving heat transfer. Graphene is incredibly thin, flexible, and long-lasting, which are all desirable qualities of a condom. A "super condom" that combines graphene and latex is currently being developed by researchers. Among the funding the initiative has received is one from the Bill & Melinda Gates Foundation. To increase feeling, the Manchester team is combining graphene with latex, which is the most common material used to make condoms. Sarcotoxin Pd-functionalized GO (GO-Pd), a new condom-coating material, was created by Zare-Zardini et al. [187] and can be used to prevent STDs and unwanted pregnancies. GO-Pd demonstrated broad-spectrum antibacterial qualities against the pathogens under investigation, particularly against *Candida vulvovaginitis* and other vaginal infections. It extended beyond the antibacterial properties of pristine peptides, fluconazole, and vancomycin. Compared with pristine peptides, GO-Pd demonstrated stronger inhibitory effects on sperm motility and viability. However, the bare peptides showed no stability or action at high temperatures (>38 °C) and acidic pH. On the other hand, GO-Pd significantly outperformed the naked peptide in every test.

3.14.15. Graphene in body scans

T-waves (a wave on an electrocardiogram) are safe for the human body, unlike X-rays, and can be used for body scanning. T-waves are difficult to produce and identify; they are also referred to as THZ radiation. THZ radiation can be efficiently detected by graphene with certain adjustments and extra parts. As a result, this will eventually result in safer body scans and faster internet speeds [188].

3.14.16. Cytotoxicity of FCN

Cytotoxicity investigations have employed the methyl-thiazolyl-diphenyl-tetrazolium bromide (MTT) assay and the trypan blue assay. Cells are typically treated to 100–1000 times the amount of fully convolutional neural network (FCN) required for imaging (0.1–1 mg/mL) during a 24 h period. Then, four hours before to the end of the incubation, the MTT solution was added to each well. The produced formazan was dissolved using dimethyl sulfoxide (DMSO) once the medium was disposed of. At 550 nm, the plates' absorbance was measured. When estimating cell viability, it was assumed that, in the absence of any carbon nanoparticles (CNP), every cell in the control set was 100% vital. There is a tight relationship between the optical density and cell quantity. When employing the Trypan blue assay, MTT was substituted with 0.4% Trypan blue solution, and the vitality of the cells was evaluated by counting the stained cells five minutes later. The results show that the examined dosages have remarkably high rates of cell survival. However, a certain amount of cell death is brought on by higher concentrations, primarily due to related surface chemistry. High quantities of fluorescence-CNP can be used for imaging or other biomedical applications considering this finding [29,189].

3.14.17. GO in biomedical applications

Graphene and its derivatives are used in drug delivery systems, biosensors, tissue engineering, and in the development of brain electrodes for neurological treatments. GO is also used in bio-functionalization, antibacterial coatings, and as a substrate for tissue engineering. GO/r-GO has less toxicity because it does not specifically target healthy cells that could be used to administer drugs. Water/serum soluble sources, reducing the viability of human colon cancer cell lines HTC (Hurthle cell thyroid carcinoma)-116, skin cancer, anti-cancer medications administered using magnets [188], and biological imaging [188,189] are further examples of drug delivery techniques. Figure 6 display several biological applications.

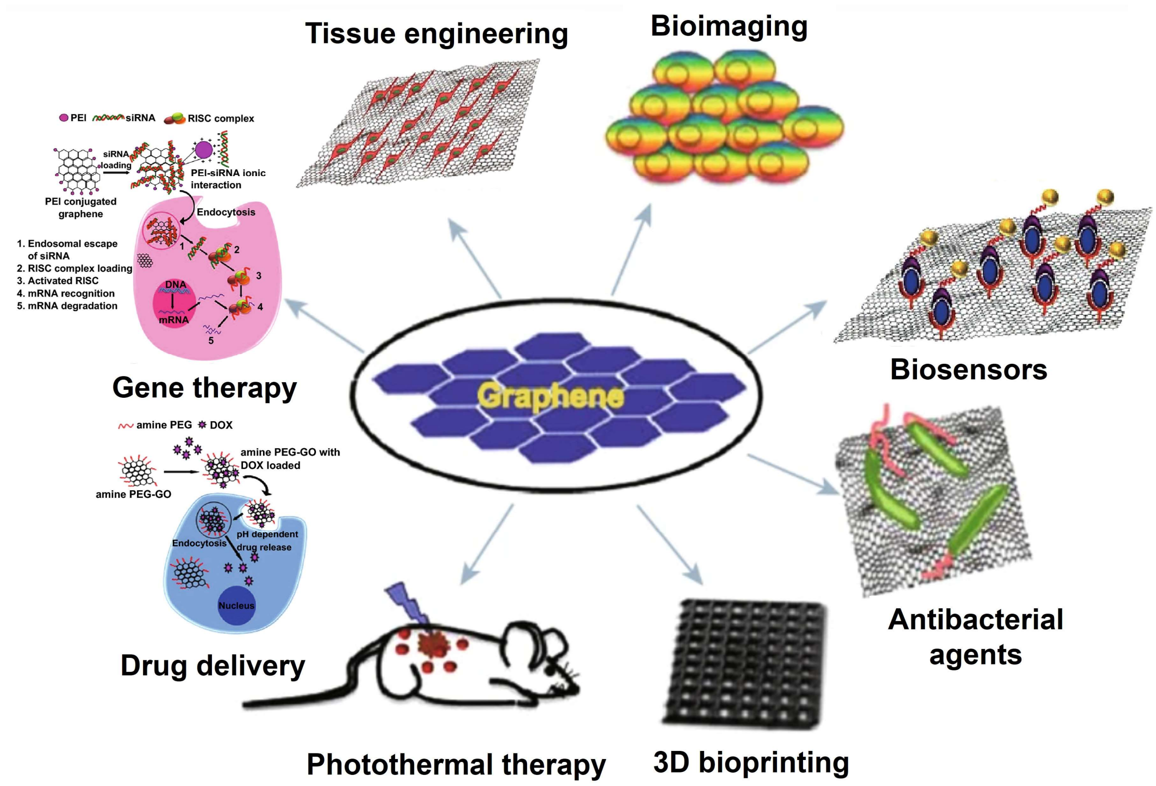

Figure 6. Different bio-applications of graphene/GO (Reproduced from Ref. [197] with permission).

3.14.18. Tissue engineering

Graphene and GO can be used as scaffolds for cell growth and differentiation, promoting stem cell proliferation and tissue regeneration. GO can stimulate myogenic differentiation in muscle tissue engineering. Graphene and GO can also be used for bone implantation due to their biocompatibility.

3.14.19. Phototherapy

Graphene and GO can be used in photodynamic and photothermal therapies, utilizing their light-absorbing properties. Photothermal therapy uses light to heat and destroy cancer cells, and photodynamic therapy uses light to activate photosensitizers that damage cancer cells. PEGylated (polyethylene glycol) GO can be used for in vivo tumor targeting and photothermal therapy.

3.14.20. Carbon nanoparticles in a bioimaging process

Water-soluble fluorescent carbon nanoparticles are considered the best cell imaging probe since they have the least amount of cytotoxicity [190–192]. However, a critical step in targeting cells and sub cells is functionalization. It is noteworthy that Ray et al. [193] found that they may be tracked thanks to their fluorescence property and that they reach cells without going through any further functionalization. Cell membrane targeting and uptake can be improved by covalently attaching an oleyl functional group to a carbon nanoparticle. In the absence of any oleyl functionalization, the labeling was insignificant, but this significantly increased cellular interaction and absorption.

Bhunia et al. [194] transformed several functional FCNs and showed their potential biological labels using conventional coating and conjugation chemistry. A well-established amphiphilic polymer coating method was used to convert hydrophobic FCN into water-soluble FCN. This technique has been used to create TAT peptide and folate-functionalized FCN via conjugation chemistry and is more suited for bio-imaging applications [195,196]. All these functional FCNs retained their fluorescence for different biological purposes. Bhunia et al. [194] investigated the efficacy of functional FCNs as fluorescent cell labels to illustrate their usefulness as imaging probes. Cells attached to cultured plates are mixed with transactivator of transcription (TAT) peptide or folate-functionalized FCNs after a few hours of incubation, and the cleaned cells are subsequently viewed under a fluorescence microscope. It has been found that cells can be labeled in one to two hours and subsequently viewed under a normal fluorescent microscope. Control studies show that FCNs have very minimal non-specific binding to cells due to their small hydrodynamic diameter and low surface charge [195]. While folate functionalization enables the selective labeling of cells expressing folate receptors, TAT functionalization encourages cell uptake and labeling [196].

3.14.21. Graphene in drug delivery

Graphene and GO can act as carriers for drugs and genes, utilizing their high surface area and ability to load materials. They can be modified with polymers or nanoparticles to enhance biocompatibility and targeting. These are extensively studied as the most promising biomaterials for biomedical applications because of their high surface area, robust biocompatibility, outstanding conductivity, and chemical and mechanical endurance. Graphene has been recognized as an effective nano-carrier for drug delivery, targeting specific cells or tissues for a variety of therapeutic chemicals due to its excellent optical, electrical, and thermal capabilities, high surface area of its planar structure, high loading potential, and mechanical and chemical stability. Functionalized graphene can be used to deliver chemotherapy drugs to the tumors of cancer patients. The graphene carriers more efficiently target cancer cells while reducing damage to affected healthy cells (Figure 6). An overview of the most promising applications of graphene-based nanocarrier surface modification methods, together with details on their biocompatibility and toxicity, was given by Liu et al. [197]. The movement of genes and anti-cancer drugs served as instances of them. Additionally, new drug delivery theories based on targeting and stimulating processes like pH, chemical interactions, thermal, photo-, and magnetic induction are investigated. A brief synopsis of the challenges and potential in this field closes the review. However, graphene and chitosan combinations have also been utilized to transport anti-inflammatory drugs, with promising results, demonstrating that drug delivery is not limited to cancer treatment [197].

3.14.22. Graphene in cancer treatment

The unique physical and chemical properties of GO/r-GO make them attractive candidates for cancer treatment. Over the last two decades, GO's interest in the biomedical realm has grown. It is a desirable option for application in biomedical fields such as tissue engineering, drug and gene delivery, biomolecule detection, and cancer treatment due to its surface functionalization and biocompatibility. By stopping the tumor from properly forming or by triggering autophagy, which kills cancer cells, graphene/GO/r-GO can detect cancer cells and stop their growth through a bioimaging process [197]. Orecchioni et al. also discovered that graphene is a cancer treatment tool [198].

3.14.23. Graphene in gene delivery

To cure certain genetic problems, gene therapy involves introducing foreign DNA into cells to distribute nucleotides to a particular cell. To increase biocompatibility, stability, cellular uptake, and gene loading efficiency, polymers and/or ligands are added to the surfaces of graphene and GO [199]. Figure 6 illustrates the use of graphene in gene delivery [197].

3.14.24. Graphene-based devices in cellular therapy

When cultivated in new GO-based devices, myeloid suppressor cells (MDSCs) taken from the donor’s body can maintain their anti-inflammatory characteristics [200]. One effective method of immune evasion control that allows tumor cells to growth unrestrained is elimination. This is demonstrated by the way graphene-based nanomaterials alter the biology of myeloid suppressor cells. Because of their adaptability, they hold promise as nano-technological tools for altering myeloid suppressor cells in a variety of clinical settings, including cancer and autoimmune disorders. By altering its physicochemical makeup, this nanomaterial can have different and conflicting biological effects on myeloid suppressor cells, either killing them or keeping them alive.

4. Conclusions

GO and pristine graphene share some similarities and have distinct applications that are dependent on synthesis process. GO is typically synthesized by oxidizing graphene, while pristine graphene is produced from graphite through various exfoliation methods. Both materials are used in sensors, electronics, and composite materials, but GO’s chemical functionality and lower conductivity make it more suitable for biomedical applications like drug delivery and bio-imaging, while pristine graphene excels in applications requiring high conductivity and mechanical strength. While both GO and graphene share some similarities in their potential applications, their distinct properties, particularly conductivity, mechanical strength, and chemical reactivity, lead to different applications in various fields. GO’s chemical functionality and lower conductivity make it suitable for biomedical applications, while pristine graphene excels in applications requiring high conductivity and mechanical strength.

Similarities:

(i) Both GO and graphene find applications in electronics, sensors, and composite materials.

(ii) Both materials can be functionalized with other chemical groups, expanding their potential applications.

(iii) Both can be prepared in various forms, including single-layer and multi-layer, and can be used in different applications depending on their specific properties.

Discrepancies:

(i) Graphene has excellent electrical conductivity, while GO has lower conductivity due to the presence of oxygen functional groups.

(ii) Pristine graphene is known for its exceptional mechanical strength, while GO is weaker due to the oxidation process.

(iii) GO is highly dispersible in water due to its hydrophilic nature, while r-GO, which is less oxidized, is less dispersible.

(iv) GO has a higher chemical reactivity due to the presence of oxygen functional groups, which makes it suitable for various chemical reactions.

(v) Pristine graphene is often preferred in electronics, transparent conductive films, and energy storage devices due to its conductivity and strength. GO is commonly used in biomedical applications, such as drug delivery and bio-imaging, due to its chemical functionality and ability to be functionalized.

However, applications for graphene and GO are at the experimental stage, even though graphene was discovered more than 20 years ago. A small number of the applications are commercially available, while others are in their infancy. Due to its remarkable charge transport, thermal, optical, and mechanical capabilities, graphene a 2D monoatomic thick building block of a carbon allotrope has gained international interest and become an exotic substance of the twenty-first century. Almost every branch of science and engineering is researching graphene and its derivatives. One of the most exciting and adaptable enabling nanotechnologies for "secure, clean, and efficient energy" is graphene. According to recent developments, graphene-based materials can significantly influence chemical sensors, energy storage, electrical and optoelectronic devices, and nanocomposites. First in the form of nano-enhanced products, then in the form of completely new nano-enabled products, graphene will provide revolutionary answers to the present industrial problems associated with energy generation and storage applications. Through pertinent proof concept demonstrators, graphene-based energy production (photovoltaics, fuel cells), energy storage (supercapacitors, batteries), and hydrogen storage systems will be created, moving closer to the desired technological readiness levels needed for industrial adoption. The graphene derivatives, GO/rGO, have various uses as well. A brief discussion of the chemistry and structure of GO/rGO may help further the scientific understanding of its nature and its applications. However, it is challenging to completely deoxygenate GO sheets with a high concentration of lattice defects, and the flaws themselves are challenging to heal after treatment. Therefore, to produce highly reducible GO, controlled oxidation is required during GO manufacturing. Future studies on GO/rGO should primarily concentrate on two areas: (i) a more thorough comprehension of the reduction mechanism and (ii) controlling graphite oxidation and GO reduction. This is because, to produce non-defective graphene and, for instance, to transform gapless semi-metallic graphene into a semi-conductor with an appropriate band gap, controllable functionalization that can modify the properties of graphene to satisfy requirements in applications is equally vital. A potential method to accomplish such modifications so that GO and rGO exhibit pronounced semiconductor-like characteristics has been inspired by earlier research on GO and rGO. We might be able to achieve good control over the attachment and removal of functional groups to certain precise sites on the carbon plane if we combine research on oxidation and reduction with a thorough grasp of graphene structure. Future studies on graphene's-controlled oxidation and reduction could help the material's use as a semiconductor in photoelectronic devices, transistors, and biomedical applications.

Finally, this review is meticulously cutting-edge research, focusing on graphene and GO practical applications in tackling emerging electronics and bio-medical applications. It is worth highlighting that there are a limited number of reviews focused on this particular subject, making this work outstanding. In this work, I identify knowledge gaps and propose future directions. Moreover, I critically analyze crucial gaps in research, including understanding the long-term environmental effects of graphene and

GO, and their interactions with diverse large-scale implementations. This review not only expands our knowledge but also guides future research endeavors in this essential field of study.

Use of AI tools declaration

The author declares that no artificial intelligence (AI) tools were used in the creation of this article.

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Conflict of interest

The author declares no competing interests.

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