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A Comprehensive Review on Graphene: Historical Development, Properties, Applications, Challenges and Future Scope

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A B S T R A C T

Graphene, due to its extraordinary properties is revolutionizing various fields. This paper explores some unusual characteristics of graphene such as mechanical properties, electrical and thermal conductance, and optical transparency. We will discuss its potential uses in various areas: super-strong composites for ultra-light and extra-durable materials and next-generation gadgets where graphene exposure might offer improved speeds. In addition, the possible applications of this nano-material in developing novel clear and flexible touch panels and advanced water filtration technologies are explored. But there are also problems with increasing output, maintaining the quality, and managing safety and health aspects despite its great potential. The paper also discusses the probable future impact of graphene on the sector of medicine, the usage of renewable energy, smart communities, and more. This analysis enhances the identification of graphene as a future wonder material by highlighting the state of research, the application of the material, and the opportunities as well as the challenges that the field has and will encounter.

1. INTRODUCTION

Graphene is an atom-thick sheet of carbon atoms in which the carbon atoms form a hexagonal lattice pattern [1, 2]. To understand this, think of graphite, the material used in pencil lead, it is made up of carbon atoms arranged on top of each other in several layers [3]. Graphene is obtained when one of these layers is peeled off. This basic structure gives graphene some peculiar characteristics. Fig. 1 shows the arrangement of atoms in graphene.

This unique structure is solely responsible for the various properties exhibited by graphene. The hexagonal structure of these atoms in a two-dimensional plane gives it high strength as well as flexibility [4]. One carbon atom in graphene links to three more carbon atoms, and this creates a hexagonal lattice which is tightly packed and the whole unit is only one atomic layer thick [5]. That is the structure that gives graphene such extraordinary features such as strength, conductivity and other features that set graphene apart from any other material.

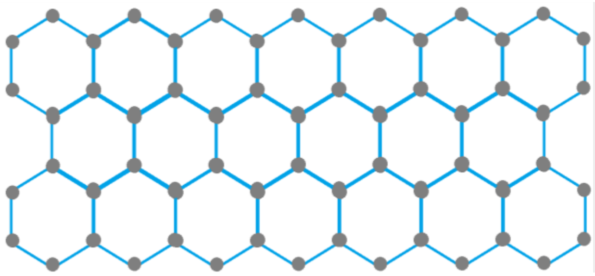

Fig. 1. Arrangement of atoms in Graphene [1].

Fig. 2 shows the timeline of graphene's research.

2. PROPERTIES OF GRAPHENE

2.1 Super Strong

Graphene is stronger than steel, and it has been cited as the strongest material in the world [8]. The mentioned quality has originated from the stable carbon-carbon bonds within its molecular structure [9]. Graphene can withstand enormous loads even if its thickness is only one atom [10]. A layer of graphene as thin as a plastic sheet can support an elephant balancing on a pencil on its surface [11]. This extraordinary strength has the potential to transform businesses that depend on robust materials. For example, adding graphene to concrete could result in stronger buildings that are also more resilient to environmental stresses like strong winds and earthquakes [12].

We use Young's modulus to measure the stiffness of a material. Therefore, the strength of graphene is also quantified by its Young's modulus. Graphene's Young's modulus is approx. 1 terapascal (TPa), which is much greater than steel [13]. That indicates that graphene is not prone to deformation under severe stress. The tensile strength of any material is the maximum amount of tensile stress that it can withstand while being stretched or pulled before breaking. The tensile strength, of graphene, is also extraordinarily high, at around 130 gigapascals (GPa) [13]. Because of its low density and excellent strength, graphene is a great option for applications where durability and weight are important considerations.

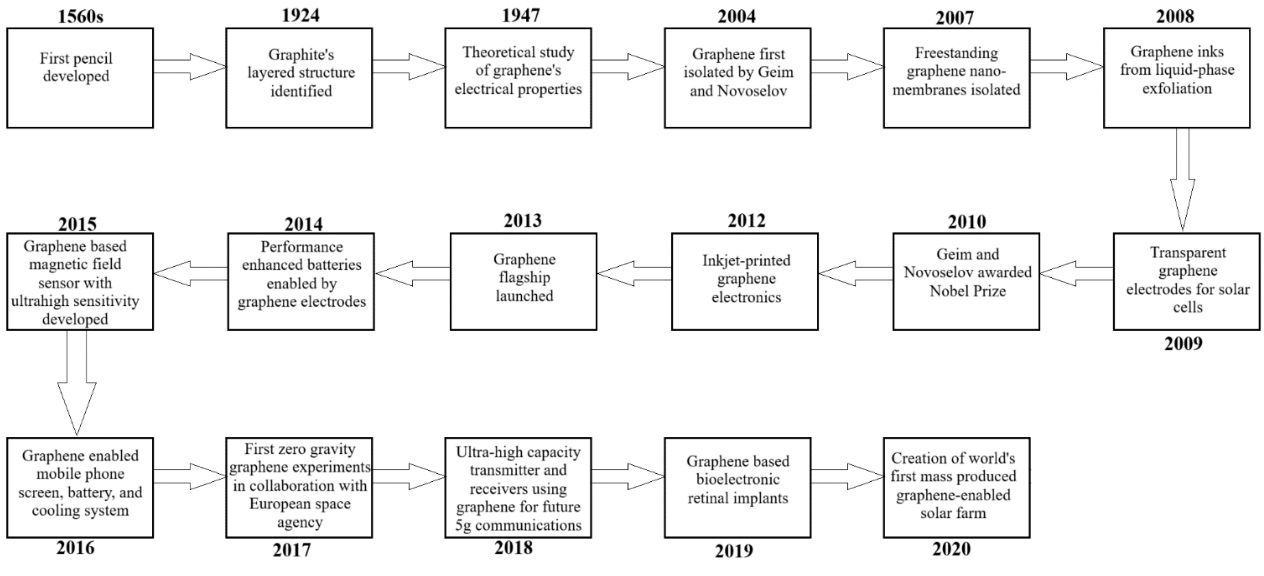

Fig. 2. History of Graphene [6, 7].

2.2 Electrically Conductive

Graphene conducts electricity exceptionally well because it offers very little barrier to the flow of electrons [14, 15]. Copper the metal traditionally used for electrical wiring is outperformed by graphene in terms of electrical conductivity [16]. This high conductivity has the potential to revolutionize the electronics industry by enabling faster and more efficient electrical devices. The next generation of computers and smartphones may use graphene-based transistors, which might result in processors that are significantly faster and more energy-efficient than those seen in silicon-based technology today. The effect of graphene content on DC electrical conductivity is shown in Fig. 3.

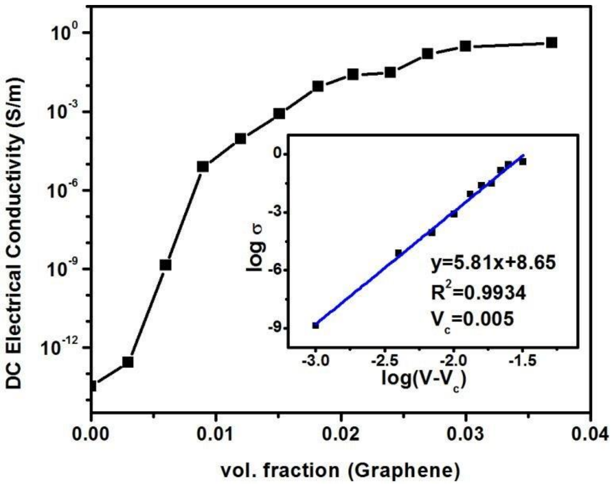

Fig. 3. Effect of graphene content on DC electrical conductivity [17].

Graphene's electronic band structure accounts for its remarkable electrical conductivity. The valence band and conduction band of graphene meet at the Dirac points, resulting in a zero bandgap [14]. As a result, electrons can act like massless Dirac fermions and pass through materials quickly and with little scattering [18]. These charge carriers can move more than 200,000 cm^2/Vs in graphene, which is much higher mobility than in silicon [19]. For this reason, graphene is perfect for high-speed optoelectronic and electronic devices including transparent electrodes, photodetectors, and transistors.

2.3 Highly Transparent

Graphene is an excellent conductor of electricity despite being almost invisible to the human eye [20]. Due to its great conductivity combined with transparency, an attribute that is rare in most materials, graphene is suitable for the production of Solar cells, Transparent touch screens and many others [21]. These make its optical characteristics useful in creating active displays that are sensitive, energy-saving and free from fuzziness. Additionally, due to its flexibility and thinness, graphene can be incorporated into new products such as clothing accessories and flexible electronics and portable electronics devices such as foldable mobile phones and tablets that can all be made to be strong and light [22].

It is as transparent as many other materials; it only absorbs 2.3% of visible light in a single layer [14]. This means that it is nearly the highest transparency for such a conductive material that can be recorded – about 97. 7%. Also due to its high transmittance and electrical conductivity, graphene is suitable for use in transparent conductor applications such as electrodes in OLEDs LCDs and touchscreens [23].

2.4 Excellent Heat Conductor

As it does to electricity, the same applies to the aspect of heating as graphene is well known to disseminate heat [24]. As suggested by this characteristic, it is ideal for use wherever tight control of heat is required [24]. For instance, graphene may help dissipate heat in electronics better by preventing the formation of localized hot spots, which often take a considerable amount of time to be removed, leading to enhancement of gadget efficiency and durability. The said feature is very useful in other industrial applications like automotive and aerospace industries, wherein heat management is crucial to maintaining the integrity and reliability of various components [25].

The thermal conductivity of Graphene is one of the highest among all known materials with a value that can even reach 5,000 W/mK [26, 27, 28]. Strong sp^2 bonds between carbon atoms and the material's two-dimensional structure, which permits phonons (quantized modes of vibrations) to move with little scattering, are responsible for the material's remarkable thermal conductivity [29]. In high-performance electronic devices, where excessive heat can cause decreased performance, reliability problems, and shorter lifespans, efficient heat dissipation is essential [30]. The thermal properties of graphene can be used to develop advanced thermal interface materials, heat sinks, and flexible electronics that can operate at higher power densities without overheating [31].

3. POTENTIAL APPLICATIONS OF GRAPHENE

The possibilities with graphene are endless. Fig. 4 shows the potential applications of graphene.

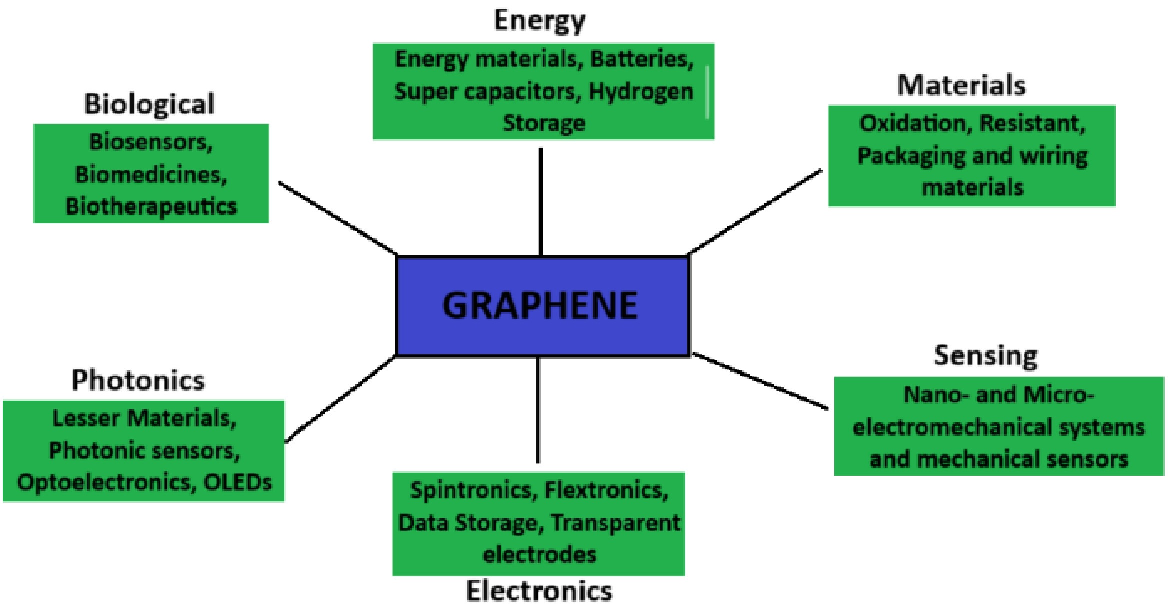

Fig. 4. Applications of Graphene.

3.1 Next-Generation Electronics

Due to the conductivity of the graphene layer, transistors could switch ON and OFF much faster and more efficiently; which would eventually lead the way to make even miniaturized yet highly powerful electronic devices [32]. Imagine computers getting more done than what could ever before be accomplished or smartphones that are faster as well as more energy conservative. Further, graphene may help in the manufacturing of flexible electronics which have the potential to enhance foldable and wearable devices [22]. In addition, there is a significant advancement being made in research concerning the ability of graphene in quantum computing which is expected to start a revolution in the means of manipulating data and its storage [33].

Graphene transistors, or graphene field-effect transistors (GFETs) can exhibit significantly high electron mobility and switching frequency [34] that may give a competing edge to silicon-based transistors. It could lead to massive enhancement of the speeds and efficiency of electronic equipment. Fig. 5 shows a field-effect transistor based on graphene.

Working towards the improvements, researchers are in the process of creating new categories of products like graphene electronic textiles, flexible displays and other potential new gadgets that could change the way we interact with technology.

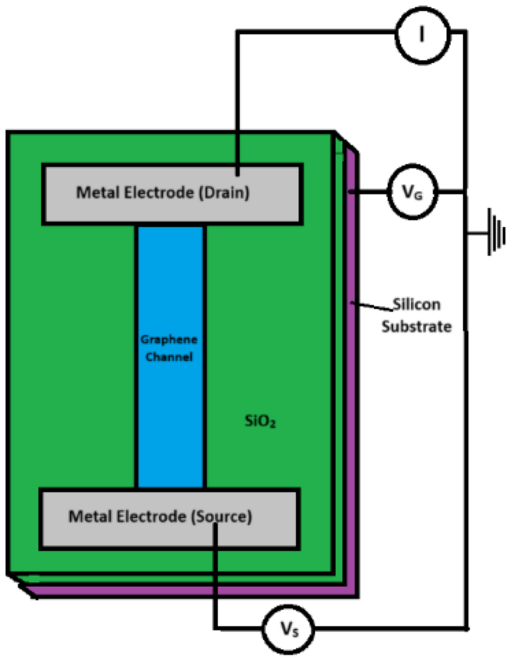

Fig. 5. Field effect transistor based on Graphene.

3.2 Super-Strong Composites

Combining or alloying graphene with other elements can produce very strong, thin, and lightweight electronic equipment [35]. It could be incorporated in several sectors such as in constructing new structures that are more durable and stronger or in producing cars that are lightweight and have lower fuel consumption [36]. Due to its ability to be tailored to have a wide variety of mechanical properties, it can be used to develop athletic equipment that provides performance improvement and durability without compromising the weight of the equipment used [37]. For example, graphene-infused tennis rackets and bicycle frames may result in enhanced sturdiness along with reduced weight and improved athletic ability.

Traditional materials including polymers, metals, and ceramics can have their mechanical characteristics greatly improved by graphene-reinforced composites [38]. With the same or even less weight overall, these composites can show increased tensile strength, fracture toughness, and impact resistance. For this reason, they are suitable for use in the building, space, and car markets. Using graphene composites when building aeroplanes could lead to lighter and more fuel-efficient planes that perform better and are safer too. Additionally, steel and concrete boosted with graphene can be used to construct infrastructure that is more resilient and structures which are stronger [12].

3.3 Superconductors at Room Temperature

Some of the current research is the research to use graphene for creating superconductors-materials that conduct electricity with zero resistivity at room temperatures [39]. Though the isolated graphene is not a superconductor, interactions with other elements or to use of such conditions as pressure and chemistry modification, or applying certain pressure, can make the graphene behave like a superconductor. Using graphene-based compounds for attaining superconductivity at room temperature holds the potential to influence several sectors. For instance, in superconducting power lines electricity transmission is done with zero loss, which enhances the effectiveness of power transmission networks. Indeed, magnets based on graphene can improve the functionality of medical imaging equipment and particle accelerators.

This finding could revolutionize energy storage and power distribution as well as make our electric networks more effective in terms of reducing energy loss. In other words, imagine that we can transmit electricity over long distances without any energy loss; this would result in significantly reduced costs on energy bills and increased security of power supplies. There might also be advancements in medical technology including better MRI machines and other diagnostic tools.

3.4 Touchscreens of the Future

Due to its high transparency and conductivity, graphene is best for making flexible and transparent items that can be used to make touchscreens of phones, tablets, and other devices [22]. This could result in the evolution of the next generation of interactive displays that are not only faster but also sturdier and smarter in terms of energy use. Think of a smartphone with a screen that can hardly get damaged or a tablet that you just fold and put in your pocket. Graphene-based touch screens can also improve the operations of wearables, making them easier and more natural to use.

The electrical conductivity of graphene, coupled with its transmittance of visible light, renders this material ideal for use in touch screens, and other related applications. Current touchscreens are utilizing indium tin oxide (ITO) which is fragile and costly [40]. That is why graphene can be a flexible, cheap alternative which maintains its conductivity even when it is bent or stretched [22, 41]. This means new opportunities for designing foldable, flexible, and even rollable electronic gadgets and equipment. Also, due to its sensitivity to touch, incorporation of graphene in touch screens will enhance their sensitivity and sharpness of touch leading to an improved customer experience [42].

3.5 Water Purification

Using graphene membranes to eliminate impurities from water could provide individuals with clean drinking water, which would be a great advantage in places lacking adequate resources [43]. This means that millions of people worldwide who cannot find safe drinking water could have their lives completely changed by this technology. For example, these filters can remove bacteria, viruses and other pollutants found in water sources and make them safe for human consumption [44]. Moreover, they can be used to purify industrial wastewater which will minimize ecological destruction and save valuable water resources.

Water can be purified and desalinated using membranes made up of graphene oxide [45].

These membranes let the water molecules pass through while they stop contaminants such as salts, heavy metals, organic compounds and pathogens. This high efficiency of graphene oxide in water filtration is because of its large surface area and controllable pore structure [46]. Furthermore, low production costs and the ability to recreate them on a larger scale for huge volumes of treated drinking supply make graphene-based filters an interesting option among other processes that may change the way we deal with the global lack of potable sources known as nature's lifebloods being contaminated at an alarming rate [47].

3.6 Energy Storage

Graphene is also a good substance for improving energy storage systems because of its high electricity and heat conduction [48]. Compared to conventional lithium-ion batteries, graphene-based batteries and supercapacitors could be more energy-dense, charge faster, and last longer [48]. Such advances have the potential to revolutionize the electric vehicle market by decreasing costs and enhancing the efficiency of electric vehicles. Additionally, Graphene-improved batteries might boost energy renewables systems through better solar or wind power storage.

3.7 Biomedical Applications

In the medical sector too, scientists are working towards finding out how graphene can be used in different areas due to its bio-compatibility and wide surface area [49]. Drug delivery systems within human bodies may use graphene as a material for making carriers that target drugs specifically to cells or tissues [50]. This can reduce side effects while increasing overall therapy effectiveness. Further still, since it is highly conductive and flexible, graphene makes an ideal material with which to produce improved biosensors capable of instantaneous glucose monitoring among other diagnostic applications including pathogen detection [51].

4. CHALLENGES IN GRAPHENE DEVELOPMENT

While graphene has enormous potential, there are still significant difficulties to overcome. Some of the biggest hurdles include:

4.1 Scaling Up Production

Scaling up the manufacturing of high-quality graphene is a major issue [52]. Although laboratory techniques enable to production of some quantities of graphene, industrial-scale production is still challenging and expensive [52, 53]. Chemical vapour deposition (CVD) and mechanical exfoliation are two current technologies that require more research in the area of producing more but maintaining quality [52]. Other processes such as roll-to-roll production and liquid-phase exfoliation are being investigated by researchers for large-scale synthesis of graphene.

(a) Chemical Vapor Deposition (CVD): This involves synthesizing graphene on a substrate, typically copper using gases reacting chemically. Even though CVD makes high-quality graphene, it is expensive to scale up. It may be possible to mass-produce using this method when changes and improvements are made [54].
(b) Liquid-Phase Exfoliation: Graphite is dispersed in a liquid and then ultrasonic energy helps in breaking down the graphite into a few layered sheets of graphene. This process produces larger quantities than CVD but it has variable quality [55].
(c) Electrochemical Exfoliation: In this technique, layers of graphene are extracted from graphite through the use of an electrochemical technique. This method provides an excellent combination of high quality and quantity and it is currently at the centre of intense research for its use in industrial products [56].
(d) Roll-to-Roll Production: Roll-to-Roll process is borrowed from the semiconductor industry that can develop graphene films on flexible substrates. Due to the high throughput and cost initialization, this technique is pleasing for mass production [57].

4.2 Cost-Effectiveness

There is another problem standing in the way of making graphene affordable for large applications. Presently, commercial products are not widely manufactured with graphene because its production costs are high [58]. Since different industries have to utilize it as a practical material, there must be ways to make its production cheap.

This will involve a reduction in the price of purifying and processing graphene alongside improvements in synthetic methods.

(a) Economics of scale: With increased manufacturing the price per unit should decrease. However, economies of scale require heavy investment both technologically and infrastructural to enable these expansions to occur through massive investments in production.
(b) Innovative Production Methods: New approaches to reducing costs are being studied by researchers. For instance, cheaper and more available raw materials, better conditions for the reaction, and better or new methods of purifying the reagents could help to decrease the costs [59].
(c) Graphene Recycling and Reuse: Creating strategies on how to recycle and reuse graphene can reduce many of its expenses. This includes developing techniques on how to recycle graphene from the composites, or devices such as consumer electronics that are used at one point in time [60].

4.3 Integration with Existing Technologies

The other hurdle is integrating the material into existing technologies and production processes. Most up-to-date technologies as well as industrial processes are based on conventional materials hence if they have to be adjusted for graphene, it would call for a lot of investment and innovation [61]. Breaking down these barriers will go a long way in ensuring that graphene achieves its full potential across various disciplines.

(a) Compatibility with Existing Materials: For any functionalities to occur, there must be some agreement between the two substances. This might be making new composites or changing the properties of graphene so that they can be compatible with other materials [62].
(b) Adapting production Processes: The use of graphene may translate to a change of strategies of production or the formulation of new strategies of production that can support its use. These may include changes in existing equipment and instruments, the layout of the process as well as, and quality assurance configurations [53].
(c) Standardization: It is crucial to establish methods for assessing and authenticating this material at the present for use in the intended application. This means developing standard conditions for the graphene's quality, thickness and other attributes [63].

4.4 Material Stability and Performance

However, the fourth and probably the most important one is the question of the stability of graphene and its composites in long-term usage. Through mechanical properties, graphene is proven to have a very high strength and hardness but is very sensitive to environmental changes and the interferences of other materials [64]. For instance, graphene which is a carbon material is known to have properties that make it oxidize and in turn, it starts to degrade its properties. There is also ongoing research by scientists on coating the material in a way that it cannot come in contact with the environment and thus be considered as redeemed.

(a) Oxidation resistance: Preserving vital qualities of graphene throughout time requires devising ways of protecting it from oxidation such as by coating it with protective layers or incorporating it into composites having higher levels of oxidation resistance.
(b) Environmental Stability: As for graphene and its composites, the capacity of the produced materials and their applicability, the ability to withstand changes the environmental conditions such as Temperature and humidity, and additional chemical exposure to the material, should be taken into consideration.
(c) Material Durability: The stability of graphene-based materials is highly critical if these materials are to be employed in long-term applications. This entails assessing and enhancing such materials for their capacity to work in real-life situations [12].

4.5 Health and Safety Concerns

Critical to understanding is the health as well as safety repercussions of graphene, just like any other innovative material. However, despite its widespread use, some issues have been raised concerning the possible toxicity of graphene nanoparticles especially when inhaled or ingested [65]. Scholars are devoting multiple efforts to carry out in-depth research and investigation regarding any potential dangers portraying a sense of health risks connected with graphene in an attempt to create protective measures and operational protocols.

(a) Toxicology studies: Fundamentally, a comprehensive study on the probable toxicity of graphene and its compounds be done. This includes investigating human health and environmental effects due to exposure to graphene.
(b) Regulatory Frameworks: Considering its safety status, clear regulations should be put in place on how it is produced, handled or disposed of [66]. This involves creating standards for employee security, environment conservation and product labelling.
(c) Public Awareness: For responsible use and elimination of misconceptions people need to be educated about possible health hazards associated with it [67].

4.6 Intellectual Property and Commercialization

Another one is an often-vague issue of IP and commercialization where clear guidance can often be hard to follow. Because of this, it is challenging to come up with new uses for graphene without violating others' intellectual property rights given the hundreds of patents for graphene-associated technologies that have already been submitted. Also, no scalable application of graphene can be done without a huge investment and going through a relatively time-consuming and complex regulatory process.

(a) Patent Landscape: When it comes to innovative practices, it is extremely important to 'get it right' the first time around by performing a proper patent search and analyzing the current state of IP to ensure revisions do not cause issues legally or in terms of opportunities for advancement.
(b) Commercialization Strategies: A complete cross-disciplinary function, maximizing commercialization is actual meaning not just coming up with new goods and services but also funding and partnership as well as adequately addressing the task of regulatory clearances.
(c) Collaborative Research: The development and application of graphene can attract cooperation and support from academic institutions, industrialists, and governments, which will foster the growth and marketplace of graphene technologies.

5. THE ROAD AHEAD

Although many technologies have shown promising performance characteristics with graphene the material is relatively new and unproven in a variety of applications. It has been found that researchers are focusing on how to increase the yield per unit cost while others are trying to optimize this material for a given use. The future of graphene is bright in terms of what is ahead of it, the fact is that there are a lot of barriers with graphene but the current progress seems positive.

5.1 Emerging Production Techniques

Scientists and engineers are also working on many new methods and ways to produce higher-quality graphene at cheaper rates. Some of these emerging methods include:

(a) Laser-Assisted Production: There are efforts to produce graphene using laser techniques with different carbon precursors. This method has advantages such as a high rate of accuracy and the capacity to freely manipulate the characteristics of graphene to be produced [68].
(b) Microbial Synthesis: There is current research being done by scientists aimed at developing microbes that can synthesize graphene. Some bacteria have innately the capacity to transform organic compounds into graphene which can be a workable and cost-effective technique [69].
(c) Electrochemical Methods: Electrochemical exfoliation and other electrochemical methods of preparation are under development for industrial-scale synthesizing. All these methods propose a satisfying compromise between quality and quantity [70].
(d) Chemical Synthesis: Alternative synthesis methodologies of chemical compounds that involve cheaper feedstocks also produce better economies of scale for the chemical industry [71].

5.2 Advanced Characterization and Testing

Graphene electronics have demonstrated much potential, however, should the material be to be utilised effectively and practically then there exists a real need for characterization and testing tools. It also defines procedures for testing its electrical, thermal, and mechanical performances on the nano-scale. Earlier, researchers could only modify the structure of the graphene and rely on their newly developed imagination to find out the responses that it generates while observing it through the metallograph, spectrograph or similar devices; the recent advancement in the microscope, spectroscopy and such alike are giving the researchers the ability to decode the response of the algorithm and how the likely an improvement of the property appropriate to the use could be managed.

(a) Atomic-Scale Imaging: Electron microscopes, which enable high-resolution vision, allow researchers to either view graphene or analyse its surface morphology with the aid of Scanning tunnelling microscopy (STM) & Transmission electron microscopy [72].
(b) Spectroscopic Analysis: In addition to XPS methods, Raman Spectroscopy provides an enormous amount of opportunity to obtain useful information about graphene [73].
(c) Mechanical Testing: Apart from the electrical measurements, other characterization techniques are used to find mechanical properties of graphene like Nanoindentation and atomic force microscopy (AFM) [74, 75].

5.3 Functionalization and Modification

Some scientists are also working as to when and how to dope and alter the specific qualities and properties of Graphene. This can either be done by altering the surface of graphene to allow the other chemical groups to attach to the surface of graphene or by compounding graphene with other materials to produce better structures.

(a) Chemical Functionalization: When doping functional groups into the graphene layer, occasionally this manipulation may alter some characteristics of graphene, for instance, solubility, reactivity, and biocompatibility. It may also continue to open new methods to other activities like drug delivery systems, sensors, and catalysts.
(b) Doping: When other types of atoms are added to the structure of graphene, the conductivity of the resulting compound is changed and these materials can act as a transistor, a sensor or an energy storage device [77].
(c) Composite Materials: Due to the ability to include graphene in other materials including polymer, metal or ceramic causes the properties of the final material like strength, conductivity and thermal stability to increase in value from the host materials [78].

6. FUTURE IMPACT OF GRAPHENE

One thing is certain: Graphene can make changes in different fields, which are in the practical application of devices and materials. With the progression of research concerning the production of graphene structures and the technologies in their production, applications of graphene will only increase. Below are some of the future uses that could result from the development of graphene:

6.1 Smart Cities

Specific application fields of graphene advanced sensors and communication equipment might have potential for smart cities [79]. They could support all-round management of infrastructures, optimal use of energy and as a result, increased safety of life in urban centres and make cities more livable. Thus, with the help of graphene sensors, it is possible to test the quality of air or water in real-time to improve the state of living in a city [80, 81]. Additionally, graphene-based communication devices could enhance connectivity and data transmission to support smart city systems [82].

(a) Environmental Monitoring: The graphene sensors can be used for environmental applications and identify the concentration of pollutants, change of temperatures and the amount of humidity. These data are useful when managing cities [81, 83].
(b) Energy Management: Super-capacitors or Graphene-based energy storage structures in combination with smart electricity networks may enhance the efficiency of electrical energy distribution in urban areas and save electrical energy plus reducing pollution [84].
(c) Transportation Systems: Graphene can be used to ensure the safety of civil structures like roads, bridges and rails by infusing construction materials with it [85, 86].

6.2 Transportation

Automotive and aerospace are another two industries that could benefit from using graphene, which encompasses the characteristics of being lightweight yet very durable [87]. The use of composites containing graphene might contribute to improving the efficiency of cars and planes, and thus decrease the amounts of gases released by cars and planes and, at the same time contribute to cutting down the costs of transport [88]. Thus, the potential application of graphene in the automobile industry can be viewed as the ability to produce lightweight and much stronger car bodies [89]. For aerospace applications, lighter components can be produced using graphene-based materials which, in turn, will help to increase the efficiency of aircraft and hence less emission of greenhouse gases [88].

(a) Automotive Applications: Graphene can be applied to the manufacturing of light and strong parts like chassis, body and battery; in this way, it increases vehicle performance and longevity [89].
(b) Aerospace Applications: Due to its strength, and lightweight nature, graphene can effectively be used for creating new generation material in aircraft & Space crafts that will increase fuel efficiency and bring down the expenses significantly [88].
(c) Electric Vehicles: The batteries made from graphene might have better energy density and less charging time which may make electric cars more acceptable and feasible [90].

6.3 Renewable Energy

Graphene can enhance the performance of solar cells windmills and other devices of energy conversion [91]. It may cause a quicker transition of systems providing renewable power and help to address the issue of climatic change. For instance, presently the concept of using graphene for the development of solar electrical cells may perhaps hold the high potential in being able to produce power with good efficiency and less cost in comparison to silicon [92]. Similarly, in terms of energy storage the nature of graphene can enable the incorporation of renewable energy into the grid and therefore contribute to the enhancement of a more sustainable society [93].

(a) Solar Energy: The application of graphene thin films in the solar cell can improve the conversion procedure, and as a result lower the costs of manufacturing solar cells to encourage the use of solar power as a renewable energy source [94, 95].
(b) Wind Energy: Graphene-based composites with better mechanical thermal and electrical conductivities could enhance the aerodynamics and mechanical properties of wind turbine blades and increase the dependability and durability of the wind power converters [96, 97].
(c) Energy Storage: Graphene will positively affect the batteries and supercapacitors as energy storage devices because they are more effective in their usage as they have higher charging speed and density of energy.
(d) Surface modification of machinery in the energy sector: Ni-based coatings, such as Ni-Cr and Ni-Al, are commonly used for corrosion protection in boiler applications due to their ability to form protective oxide layers [98-105]. However, these coatings have limitations, including high cost, potential environmental concerns, and limited thermal conductivity.

Graphene-based coatings offer several potential advantages over Ni-based coatings for boiler applications:

- Enhanced corrosion resistance: Graphene's impermeable nature and ability to form strong bonds with other materials can improve the corrosion resistance of the coating.
- Improved thermal conductivity: Graphene's excellent thermal conductivity can help dissipate heat more efficiently, reducing thermal stresses and improving the overall performance of the boiler components.
- Reduced thickness: Graphene-based coatings can be applied in thinner layers compared to Ni-based coatings, potentially reducing weight and cost.
- Environmental benefits: Graphene-based coatings might offer more environmentally friendly alternatives to Ni-based coatings, reducing the risk of heavy metal contamination [106].

6.4 Consumer Products

Examples of applications can range from using graphene in dresses to using it in sports equipment since the incorporation of graphene makes the product more efficient and resistant to wear and tear [107, 108]. Graphene has characteristics that have not been met by any other material and can result in product developments that enhance human life. For example, using graphene in fabrics may increase the strength and elasticity of the fabric to wear apparel for outdoor activities and sports [109]. Within sports, it can be used in the formulation of lighter and stronger equipment to improve performance and minimize the instances of injury [110].

(a) Wearable Technology: Due to high flexibility and processability, followed by its electrical conductivity, there is a great potential for the preparation of high-functionality flexible electronics, like wearable gadgets: multifunctional clothing [41, 111].
(b) Sports Equipment: Incorporating graphene in clothing or other articles, can lead to the production of light sportswear which are stronger and longer lasting, enhancing the performance and safety of the players [112].
(c) Consumer Electronics: It could be employed to create a new generation of smartphones and tablets and other such gadgets to work more efficiently and endure longer [90, 113].

6.5 Healthcare

Health care can benefit from such a material because graphene is a potential solution for diagnostics, drugs, and medicine applications [114]. Due to its biocompatibility and large surface area, it is the material of choice for creating emerging technologies in medicine [115]. For instance, it was noted that graphene-based biosensors could be used for continuous health status tracking, which would facilitate early diagnostics of diseases and individualized treatment [116]. Also, it has been demonstrated that graphene can be used for drug delivery, and the new method would result in better target medications and help avoid undesirable consequences [117].

(a) Diagnostics: Graphene-based biosensors allow biomarker detection with high sensitivity and specificity that will facilitate early diagnosis and continuous monitoring of diseases [118].
(b) Drug Delivery: The high surface area and biocompatibility of graphene ensure that it is the most favourable material when it comes to the production of targeted drug delivery systems that can enhance the effectiveness and safety of the compound [106, 118].
(c) Medical Devices: New generation medical instruments can be developed with the help of graphene in a way that could include flexible electronics to track patient's signs or implants to treat diseases [118].

7. CONCLUSION

It is more than just a plain material as people call it the ‘miracle material of the future,’ the discovery of graphene is capable of transforming many areas of our lives. It has wonderful features; super strength, electric and thermal conductivity, transparency and flexibility which makes it an ideal substance for various uses. However, there are five major problems to be tackled to realise this potential such as mass production, reduction of the cost of graphene material, compatibility of graphene with other materials, and the potential health and safety issues associated with graphene material.

On a concluding note, it can be said that the future is rather bright for graphene as a material of tremendous scientific interest, with studies on it being ongoing and opening doors to discoveries. Shortly, as production techniques improve, as new characterization methodologies become available, and of course, as functionalization approaches of graphene are manifest, the impact of graphene on mankind will accelerate. From semiconductors and superior battery tech to medical applications and everyday materials, the world with graphene is literally at our fingertips. The way forward may be arduous but the potential benefits are equally unbelievable, they contribute to making graphene one of the remarkable inventions in the modern world of science and engineering.

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