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REVIEW ARTICLE

Recent Advances in Graphene-based Nanocomposites for Automotive and Off-highway Vehicle Applications

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ARTICLE HISTORY

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Abstract: Nanocomposites comprised of a polymer matrix and various types of nanosized fillers have remained as one of the most important engineering materials and continue to draw great interest in the research community and industry. In particular, graphene-based nanocomposites that possess high thermal conductivity and excellent mechanical, electrical and optical properties have turned out to be promising fillers for making the next generation high-performance composite materials.

The automotive and off-highway machinery industry is viewed as the one in which the highest volume of advanced composite materials such as graphene-based nanocomposites will be used in the future to produce lighter, stronger, safer, and more energy-efficient vehicles. Considering the mechanical, functional and interface properties of the graphene and polymer matrix under severe loading conditions, largescale production of the graphene-based nanocomposites in automotive and off-highway machinery applications is challenging. The problem is attributed to the nonlinear properties, joining of dissimilar materials and the high demand for computations. Graphene-based material strategies have been investigated and demonstrated to be effective for structural applications in various industries including electronics, electromechanical and energy systems. However, currently, there is only limited research highlighting the specific knowledge available for design engineers and researchers involved in providing lightweight but strong solutions with the use of graphene-based materials for automotive and off-highway vehicle applications.

The present review presents an overview of the latest studies that utilize graphene-based nanomaterials and their composites in automotive and off-highway machinery applications. Firstly, the paper describes the concept of traditional composites used presently in the engineering industries by considering its advantages and limitations. Then, it highlights the key benefits of using nanostructured carbon materials, such as graphene, through some recent studies available in the literature. Subsequently, it depicts the various mechanisms of integrating graphene as polymer reinforcements within the composite materials based on the survey and their related modelling, designing, and manufacturing capabilities suitable for the automotive and off-highway machinery industry. Finally, it outlines the available experimental evidence for graphene-based composites. To lay the groundwork for future work in this exciting area, the paper discusses the current challenges as well as future prospects in the field.

Keywords: Automotive off-highway vehicle, graphene, nano-composites, polymer matrix, thermal conductivity, zero climbing resistance.

1. INTRODUCTION

All major global automotive and off-highway vehicle markets have stringent legislation focused on controlling carbon dioxide (CO_2) and exhaust gas emissions, such as particulates and nitric oxide (NOx), for improving the fuel economy. There are many ways to enhance vehicle fuel economy, and one of the techniques is to reduce the driving load by lowering the inertial forces (weight) and resistances (aerodynamic drag, tire rolling resistance) encountered by the vehicle. This action reduces the propulsion requirement of the engine and decreases the fuel energy needed to move the vehicle over a given distance. Key parameters that contribute to a vehicle's fuel consumption can be examined by the relationship given below [1]:

$$FC = \frac{\int b_e . P dt}{v dt} = \frac{\int b_e \left(\frac{F_t v}{\eta}\right) dt}{\int v dt}$$

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where FC = Vehicle's fuel consumption [L/km]

b_e = Engine's specific fuel consumption [L/kWh]

P = Engine power output [kW]

t = Time [s or hr]

v = Instantaneous vehicle speed [m/s or km/hr]

F_t = Tractive force [kN]

η = Drivetrain efficiency

With zero climbing resistance, the tractive force would be the sum of the tire rolling resistance, acceleration or braking resistance, aerodynamic drag and climbing resistance. The forces acting on an accelerating automotive and off-highway vehicle on a level road are shown in Fig. (**1**).

As lightweight materials are capable of increasing vehicle fuel efficiency by 6%-8% for each 10% reduction in weight, government regulations, such as corporate average fuel economy (CAFE) standards in the US and carbon emission targets in Europe, are the key drivers for putting pressure on the original equipment manufacturers (OEMs) to incorporate lightweight materials and minimize the overall weight. Therefore, the new generation vehicles must be lighter, less polluting and more fuel efficient. Hence, a carbon footprint has become an important parameter for designing such a vehicle. OEMs have been finding varied and creative solutions to reduce the CO_2 output and augment the environmental friendliness while retaining the affordability and safety aspects. Among these, weight reduction by employing multifunctional advanced materials is one of the most promising areas [2]. However, significant hurdles exist with respect to manufacturability, improved performance, modelling, and cost for such multifunctional advanced materials. As a consequence, considerable material science efforts are needed to overcome these obstacles. The discovery of the graphene with its interesting physical and mechanical properties has unlocked an encouraging window for designing advanced light nanocomposites [3].

Recently, graphene has attracted both academic and industrial interest because it can produce a dramatic improvement when added as a reinforcing agent to a polymer matrix. As reported by most of the researchers in this field, graphene-based polymeric composites have improved the overall performance and properties such as tensile strength / elastic modulus [4], electrical conductivity [5], thermal conductivity [6] and thermal stability [7] at low filler content. The material is expected to have immense applications in field-effect transistors [8, 9], electromechanical systems [10, 11], thermal modulators [12], ultracapacitors [13], semiconductor photocatalysts [14, 15], strain sensors [16, 17], flexible and stretchable electronics [18], supercapacitors [19-21], energy materials [22], bioimaging [23], sodium iron batteries [24], *etc*. The most immediate use for graphene-based products as structural materials is in the automotive sector [25-29].

The exploitation of graphene is highly difficult [30] in some applications owing to its 2D-planar structure and the fact that it is a zero-gap semi-metal. Furthermore, techniques for its mass production are limited to the liquid medium and require graphene stabilization and solvent removal, thereby resulting in very low yields [31]. For this reason, graphene has been processed into different forms such as nanoplates, nanodiscs, branched structures, nanoprisms, nanosheets, nanowalls [32] nanoribbons [33] and quantum dots [34] for use in energy applications as well as hydrogels [35] and foams [36] for biological and energy applications. Other key concerns are the dispersion of the material in the polymer matrix and the interaction between the graphene filter and the polymer. Hence, the application of the product is still a challenge and the most important problem lies in the preparation of high-quality and well-defined graphene in bulk quantities.

Most of the articles and reports are based on research undertaken using scale models of graphene-modified composites prepared in the lab. Besides, there has been a limited application of graphene-based materials in the automotive and off-highway vehicle sector. Furthermore, research activities are underway for studying the potentiality of these systems, especially in next-generation off-highway vehicles. To aid the studies conducted in the field, this paper provides a comprehensive review of relevant literature.

2. THE CONCEPT OF GRAPHENE-BASED POLYMER COMPOSITES

2.1. Advanced Composites

Composites are those that consist of strong carry-load materials (commonly referred to as reinforcement) which are embedded in the matrix to combine the beneficial properties

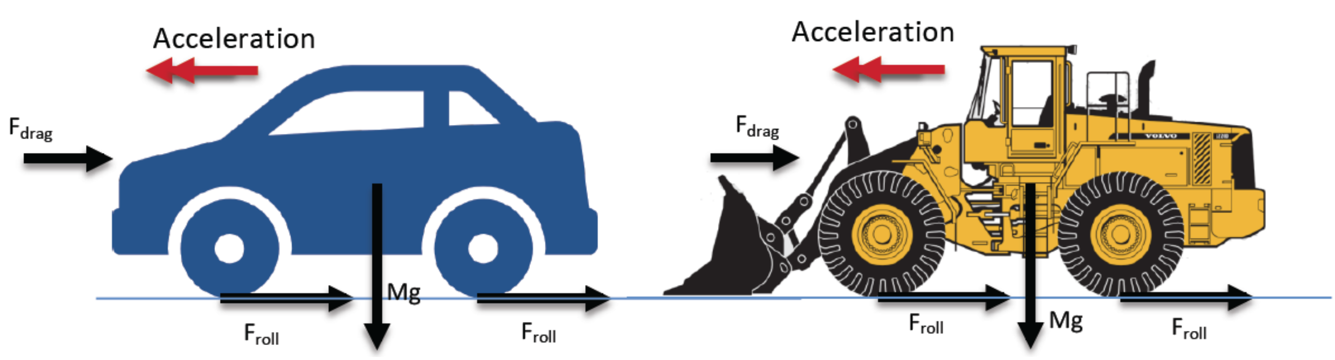


Fig. (1). Forces on an accelerating automotive and off-highway vehicle on a level road. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

of the constituent materials and produce polymer matrix composites (PMC), ceramic matrix composites (CMC) and metal matrix composites (MMC) as shown in Fig. (**2**). The reinforcement provides the strength and rigidity that is needed to support the structural load as depicted in Fig. (**3**).

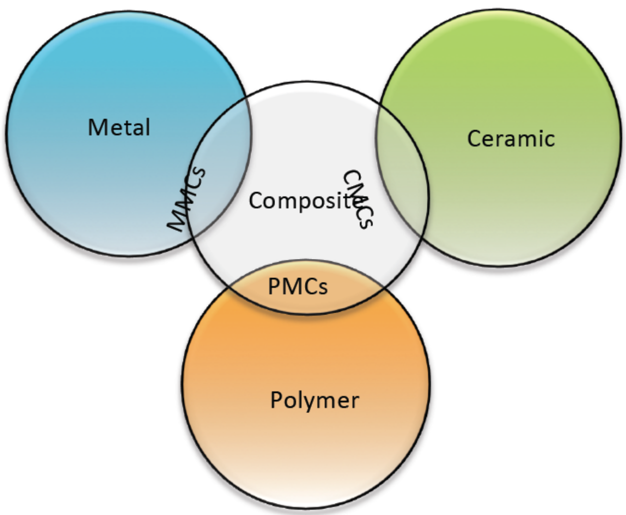


Fig. (2). The family of composites among metals/ceramics/polymers. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

In recent times, advanced composites [38] are finding extensive applications in various industrial sectors such as aerospace [39], next-generation spacecraft [40], automobiles [41, 42], civil engineering [43], marine [44], *etc*. These products are often classified according to the type of matrix or the physical form of the reinforcing material as given in Table **1**. The primary advantages of advanced composites that make them very attractive for these applications are low weight, high specific strength, excellent thermal stability as well as low creep and stress relaxation.

2.2. Laminar Composites

A single layer of a fibre-reinforced composite is called a lamina [45]. When layers of lamina are assembled as illustrated in Fig. (**4a**), the resultant material is called a laminate or more popularly a laminar composite. Sandwich structures fall under this category (Fig. **4b-c**).

2.3. Functionally Graded Materials

Functionally graded materials (FGMs) are the advanced composites [46] which have continuously varying material compositions and properties through certain dimensions of the structure to achieve the desired goals.

The aforesaid traditional composites have immense advantages such as directional tailoring capability, high 'strength or stiffness to weight' ratio, durability and resistance to corrosion. However, they are often made into a laminate structure consisting of different ply layers, and "delamination" can occur between the layers which are weak. Delamination and cracks in composites are mostly internal and hence require complicated inspection techniques for detection. Metals expand and contract more with temperature variations than the composites. This may cause an imbalance at the joinery and lead to failure. Nevertheless, barring such disadvantages, composite materials are almost perfect for many industries and fulfil most of the structural requirements.

2.4. Journey from Carbon Materials to Graphene and Further

In this nanotechnology era, carbon materials play many important roles in human life right from the basic day-to-day products to advanced applications in science and technology. Nanostructured carbons make up a substantial part of materials science. Fullerenes, carbon nanotubes and graphenes are probably the most prominent examples. Graphene is a two-

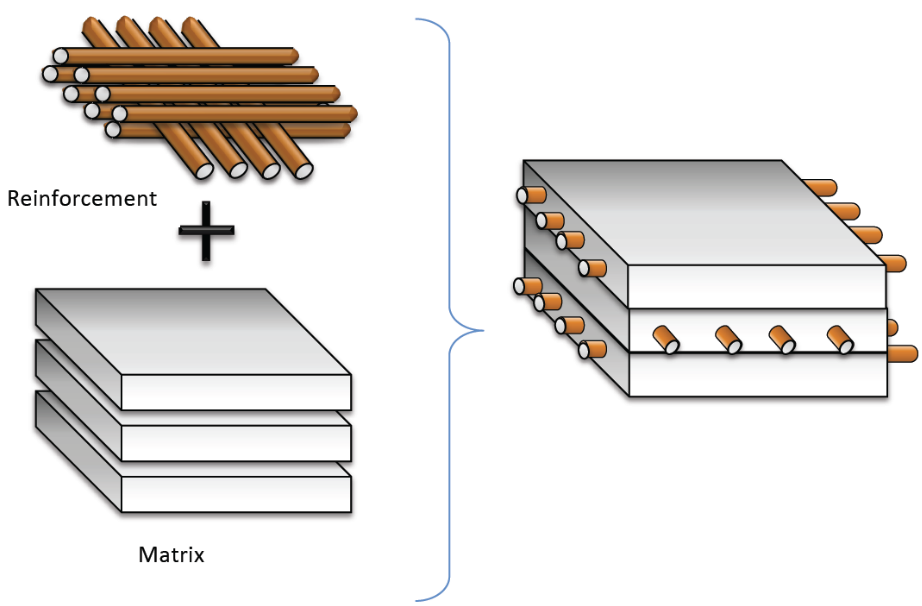
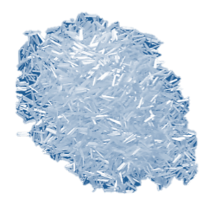


Fig. (3). Composition of composites [37]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Table 1. Classification of advanced composites.

Type of Matrix Material	Physical form of Reinforcing Material
Polymer Matrix Composites (PMCs) *e.g.*, polyester, epoxy, bismaleimide, phenolic matrices	*Particulate:* roughly spherical reinforcing particles with diameters ~ 1-100 µm 
Ceramic Matrix Composites (CMCs) Metal Matrix Composite (MMC) is a material consisting of a metallic matrix combined with a ceramic (oxides, carbides) or metallic (lead, tungsten, molybdenum) dispersed phase. *e.g.*, silicon carbide (SiC), silicon nitride (Si_3N4), aluminum oxide (Al_2O3) matrices	*Whisker:* Whiskers are very thin single crystals that have extremely large length-to-diameter ratios. diameters ~ 5-30 µm, lengths < 10 mm *e.g.*, graphite, silicon carbide, silicon nitride, and aluminum oxide 
Carbon-Carbon Composites (CCCs) Carbon matrix composites consist of carbon as matrix and carbon fibres as reinforcement (both matrix and reinforcement are carbon). 	*Short (or "chopped") fiber:* diameters ~ 5-30 µm lengths 10 → 200 mm 
Metal Matrix Composites (MMCs) Metal matrix composites (MMCs) are the class of materials in which high strength and high modulus refractory ceramics are reinforced with the ductile metal matrix. Matrices commonly used are light metals such as aluminum, magnesium, copper, titanium and zinc while the reinforcements are ceramics like carbides, oxides, nitrides and borides.	*Continuous fiber:* diameters ~ 5-30 µm lengths, in effect, infinite  

dimensional matrix of carbon atoms arranged in a honeycomb lattice [47]. A single square-meter sheet of graphene would weigh just 0.0077 grams but could support up to four kilograms [48]. Hence, it is a suitable example of a novel material that has been acclaimed for its amazing strength, flexibility and electrical conductivity. It is estimated to be approximately 100 times as strong as steel [49] and can heal itself if free carbon atoms are nearby and available. This is probably why scientists and researchers call it "a miracle material" and predict that it will revolutionize just about every industry known to humans.

Key properties of graphene and its derivatives include:

- Graphene could be considered as the world's strongest material. Its specific strength is 48 000 kN m kg^{-1}, which is over 300 times higher than that of steel (steel specific strength = 154 kN m kg^{-1}); yet, it is extremely lightweight [50].
- Graphene has a carrier mobility of up to 10,000 cm^2 V^{-1} s-1 and thermal conductivity of 3000-5000 W m^{-1} K^{-1} at room temperature. Besides, it has a high surface area of ~2630 m^2 g^{-1}, good optical transparency of ~97.3% and excellent mechanical strength with Young's modulus of 1.0 TPa [51].
- Graphene can be readily functionalized chemically, making it very handy and allowing it to be incorporated into a range of devices and materials to suit the wished-for application.

Different properties of graphene that have been experimentally evaluated by several researchers in the last decade are summarized in Table **2** [52].

Some of the major disadvantages of graphene [53]:

- It is an excellent conductor of electricity and does not have a bandgap (cannot be switched off). Researchers are working to fixing this issue.
- It is susceptible to the oxidative atmosphere when used as a catalyst.

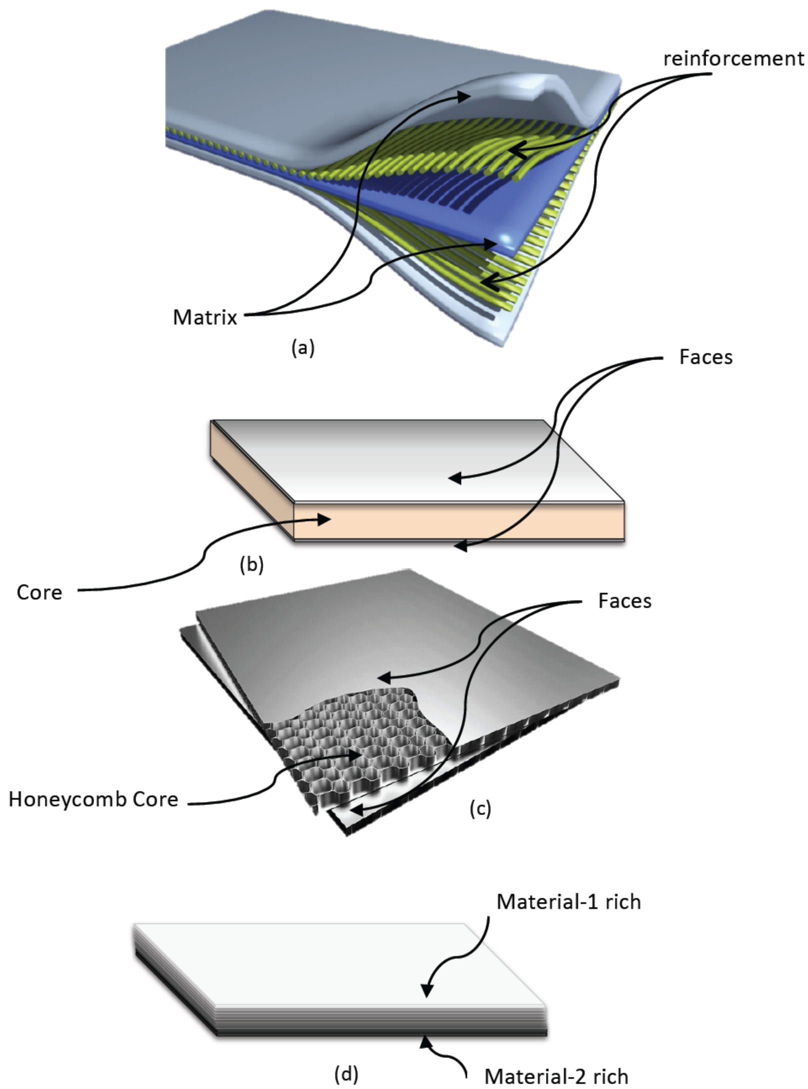


Fig. (4). Typical advanced composites (**a**) Laminate (**b**) sandwich (**c**) Honeycomb based sandwich (**d**) Functionally graded materials [46]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Table 2. Physicochemical properties of graphene family nanomaterials [52].

Property	Single Layer Graphene	Graphene Oxide (GO)	Reduced Graphene Oxide (rGO)
Young's modulus (Tpa)	1.0	0.208 ± 0.023	0.25
Tensile strength (Mpa)	130×10^{3}	76.8 ± 19.9	0.9×10^{5}
Fracture toughness (Mpa)	4-5	-	2.8-3
Optical transmittance	97.7%	-	60-90% depending on the reduction agent and fabrication method
Charge carrier concentration (cm^{-2})	1.4×10^{13}	-	-
Room-temperature mobility ($cm^2\ V^{-1}\ s^{-1}$)	~200,000	2-200	17-2000
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	1500-5000	2000 for pure 600 on Si/SiO_2 substrate	30-250
Electrical conductivity (S/cm)	10^4	10^{-1}	666.7
Energy gap	0.26	-	Tunable gap of 0.35-0.78
Surface area ($m^2\ g^{-1}$)	560.6	~2630	-

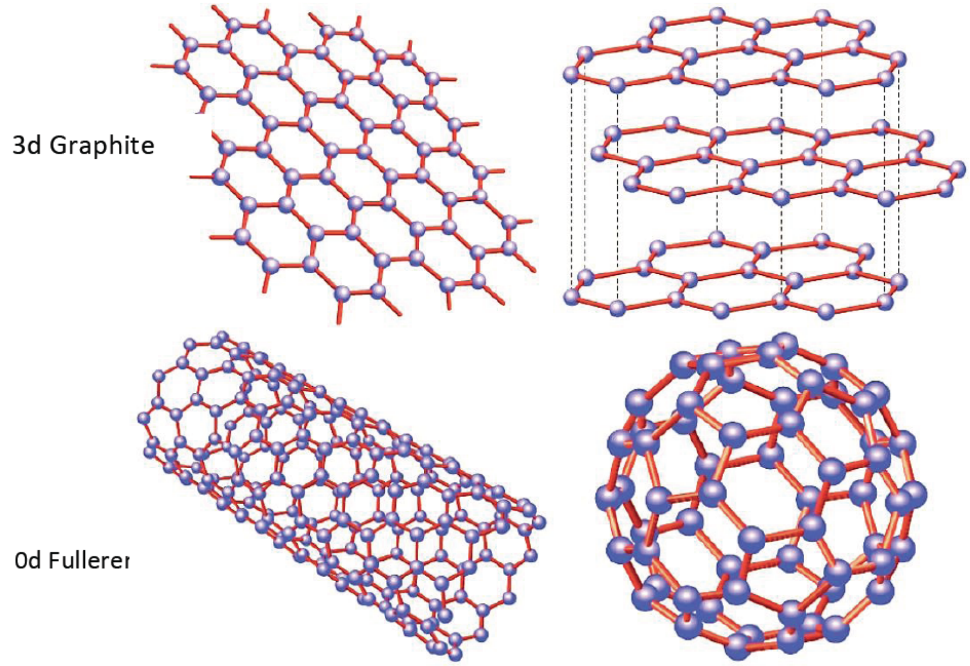


Fig. (5). Mother of all graphitic forms [32, 58, 59]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

- It demonstrates some toxic qualities.
- Its jagged edges can easily pass through cell membranes, enter the cell and disturb its normal functions.

These are just a few of the advantages and disadvantages of the 'wonder material'. Since the product is still in the research stage, much more is yet to be revealed [54]. Graphene is considered as a basic building block of other carbon-based allotropes; it can be wrapped around to form 0d fullerenes, rolled to form 1d carbon nanotubes (CNTs) and stacked to form 3d graphite (Fig. **5**). Owing to the industrial and academic significance of carbon allotropes, there has been an increasing interest in recent years in discovering more two-dimensional (2D) carbon allotropes by manipulating the carbon atom or C-C bond in graphene, including the rotation of C-C bonds, the extension of C-C bonds, and the rearrangement of C-C bonds as demonstrated in Fig. (**6**). Several articles have been published on the well-studied carbon allotropes [55-57]. Hence, their details have not been included here. Instead, this review primarily emphasizes the graphene-based composites that have been explored in the past decade.

Fig. (**7**) shows a compressive strength-density Ashby chart. The theoretically achievable limit is indicated. The lower bound is defined by diamond, which has the highest specific strength of all bulk materials, and the upper bound is given by the strength of CNTs and graphene, which represent the highest strength values measured so far. Graphene seems to be suitable for use as a strengthening layer between other materials such as polymers. It appears from the literature that graphene-based composites have many major advantages over traditional composites and thus have emerged as attractive candidates for fillers. Their increased specific interfacial area enables potentially higher interfacial interactions and hence higher modulus. Hence, graphene is being added to numerous materials to make them more lightweight and stronger.

For the aviation, shipbuilding and other engineering sectors such as automotive and off-highway vehicles, a composite material which is much lighter than steel but still provides the required strength will save the expenses related to fuel consumption; therefore, graphene is now being combined with such materials. These structural composites have a massive potential to become extensively used substitutes for a range of materials that are currently used. The presence of graphene can enhance the conductivity and strength of bulk materials and help create composites with superior qualities. The material can also be added to metals, polymers and ceramics to make composites that are conductive and resistant to heat and pressure. The applications of the substance seem endless as the graphene-polymer composite proves to be light, flexible and an excellent electrical conductor. It can be used to enhance the efficiency of photocatalysts and can be combined with existing products, the so-called composite materials, to make all kinds of advanced composites. The utilization of graphene composites encompasses medical implants, electronics, battery technology, engineering materials for aerospace, automotive, heavy vehicles and much more. Fig. (**8**) depicts the Ashby plot of Young's modulus against tensile strength. It compares the mechanical properties of the conventional polymer composites, including glass fibre-reinforced plastic (GFRP) and carbon fibre-reinforced plastic (CFRP), with the CNT or graphene-based polymer composites described by Kinloch *et al.* [61]. Thick outlines represent the families of each material. It is evident from the projected Ashby plot that the mechanical properties of CNT or graphene polymer composites are scattered around those of the GFRPs and polymers.

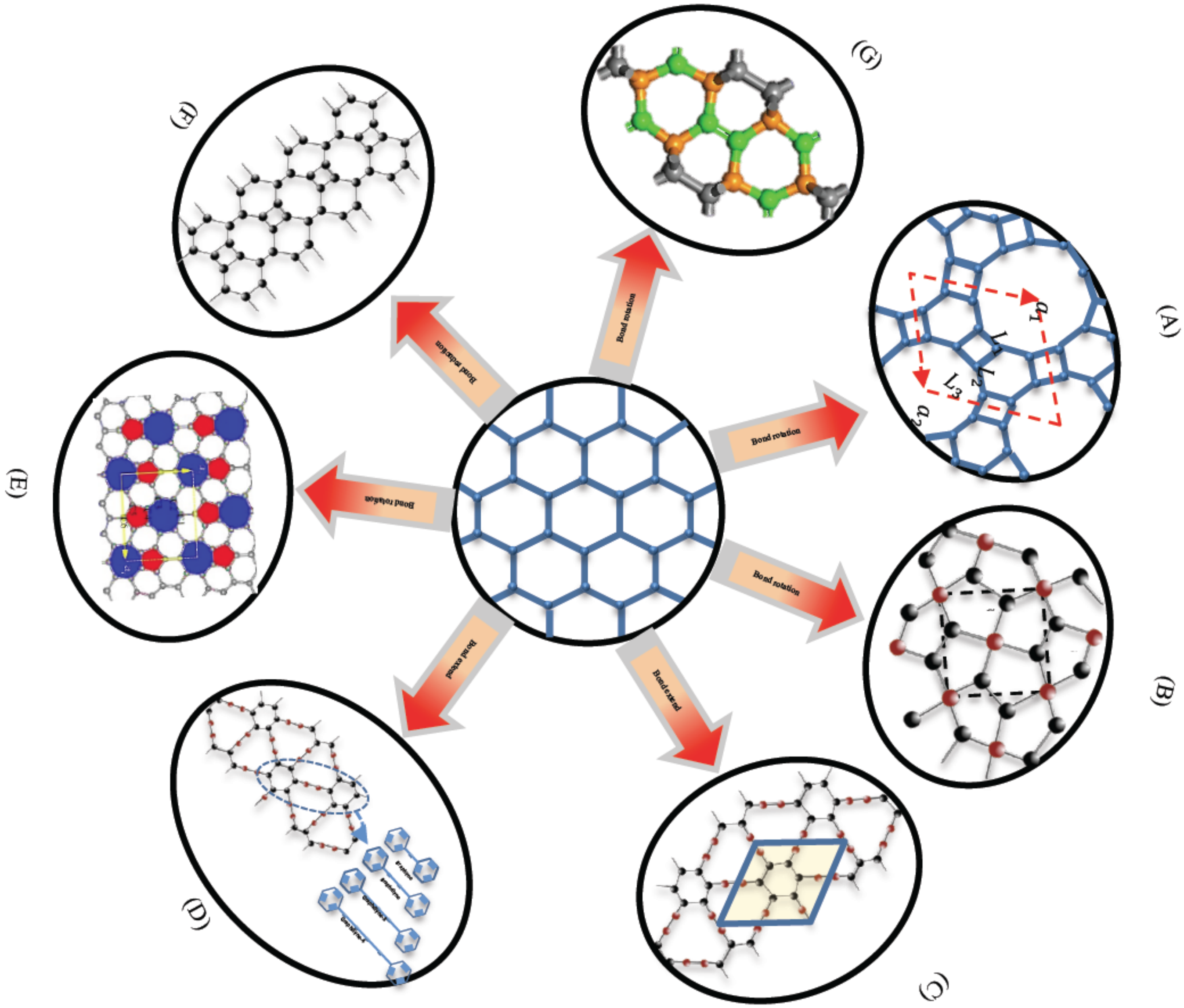


Fig. (6). Carbon allotropes are designed by manipulating the carbon atom or C-C bond in graphene, including the rotation of C-C bonds, the extension of C-C bonds, and the rearrangement of C-C bonds. These carbon allotropes are (**A**) graphenylene; (**B**) penta-graphene; (**C**) twin grapene; (**D**) graphyne; (**E**) phagraphene ; (**F**) biphenylene ; (**G**) H18 carbon [59]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

However, the mechanical properties of CNT spun fibres suggest that CNT or graphene fibres can replace carbon fibres and if properly designed and manufactured, the continuously reinforced CNT or graphene spun fibres composites could be exploited for making ultralight yet super strong structures in the near future.

As represented in Table **2**, single-layered graphene is still considered as one of the strongest fillers; however, further alteration of the substance can be a viable method for forging a strong interaction between graphene and the polymer of interest. Graphene can be modified by using covalent and non-covalent methods. However, the originality of graphene typically gets distorted, which compromises its thermal and mechanical properties. The physicochemical properties of the nanocomposite depend on the distribution of the graphene layers in the polymer matrix as well as on the interfacial bonding between the graphene layers and the polymer matrix. Fig. (**9**) displays the different types of graphene-based polymer composites that have been reported in the literature [62].

The research on graphene, including production methods and future opportunities for industrial applications, has grown exponentially since 2004. Over the years, several works have been published on graphene synthesis techniques [63-74]; hence, the details are not covered here. However, this section summarizes the production techniques that are currently being used. Fig. (**10**) provides an overview of the various techniques for graphene synthesis based on top-down and bottom-up approaches. Furthermore, the illustration of the main graphene production methods has been provided in a picture format by Bonaccorso [75].

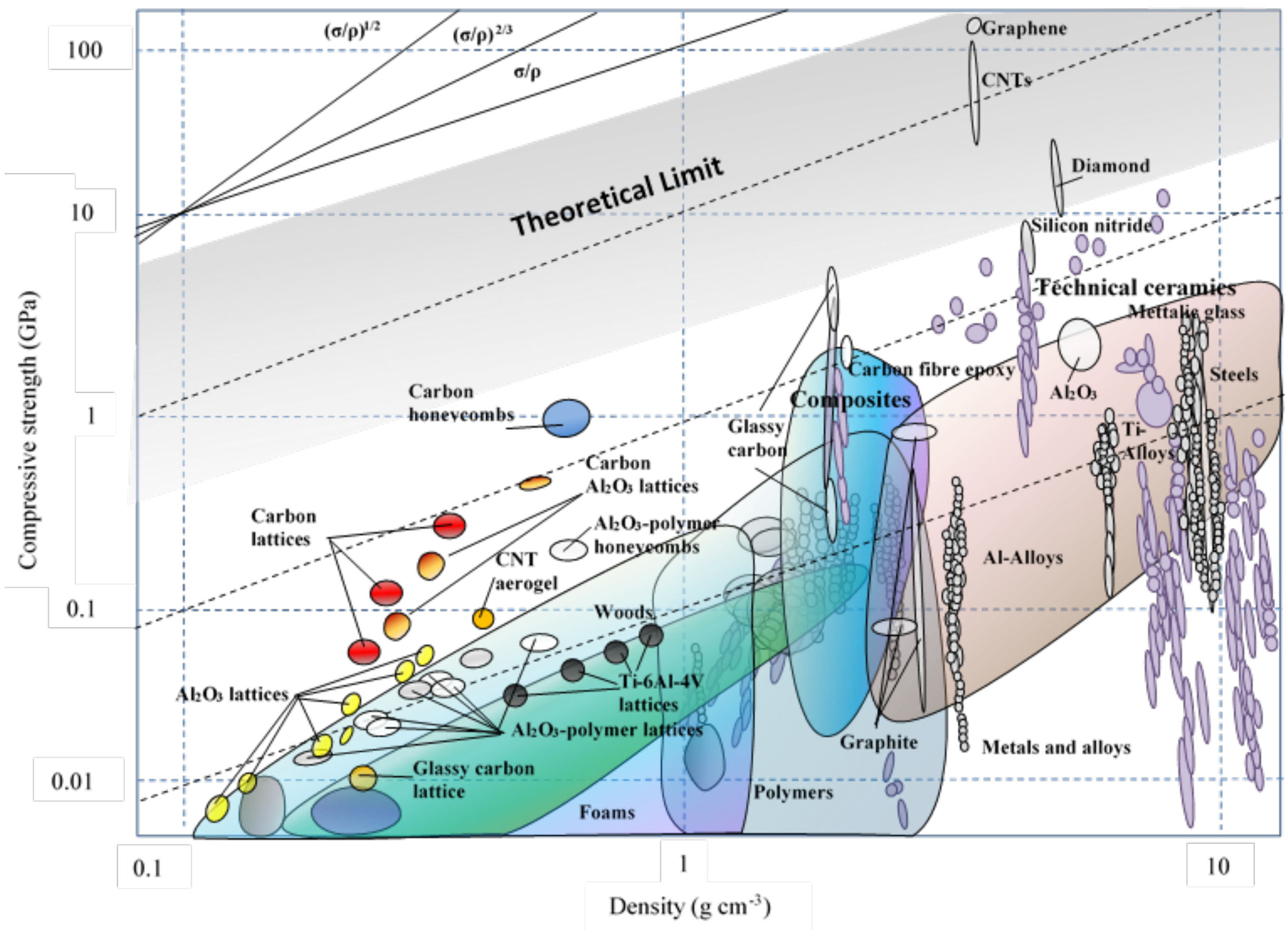


Fig. (7). Compressive strength-density Ashby chart for different materials [60]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

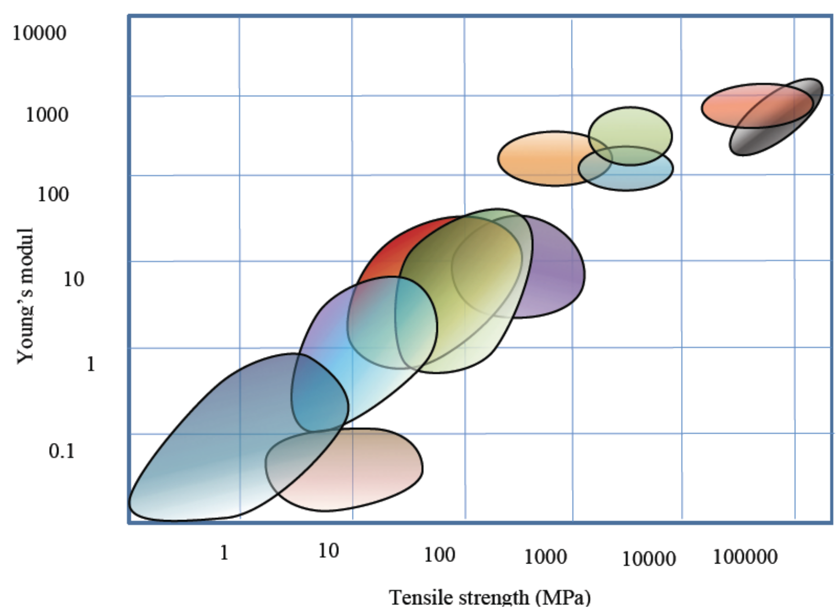


Fig. (8). Ashby plot of Young's modulus plotted against tensile strength comparing the mechanical properties of conventional polymer composites, including glass fiber-reinforced plastic (GFRP) and carbon fiber-reinforced plastic (CFRP), with CNT or graphene-based polymer composites [61]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

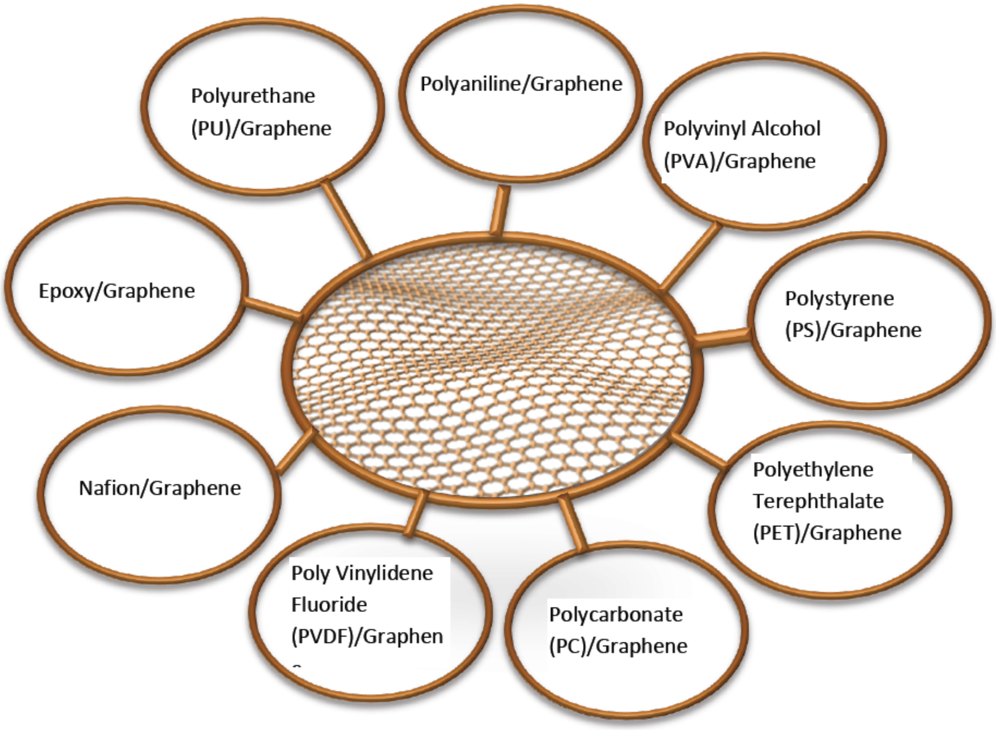


Fig. (9). Different types of graphene-based polymer composites [62]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

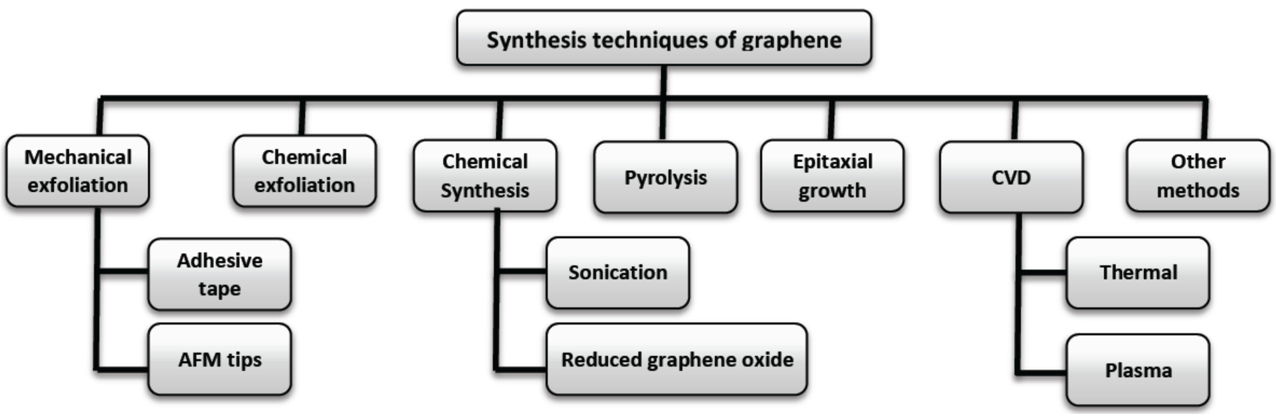


Fig. (10). Various techniques used for graphene synthesis [53]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Recently, Bae *et al*. [76] reported the roll-to-roll production of 30-inch graphene films using the CVD approach, and Fig. (**11**) shows the schematic of the roll-based production of graphene films grown on a copper foil. The fabrication process consists of three steps after the synthesis of graphene, namely: (i) adhesion of the polymer supports to the graphene on the copper foil; (ii) etching of the copper layers; and (iii) release of the graphene layers and their transfer onto a target substrate.

The advantages and disadvantages of the current techniques to produce graphene are presented in Table **3**.

2.5. Challenges and Openings in Graphene Commercialization

One can observe from the study by Ren *et al*. [77] that the past 6-7 years have witnessed a steady worldwide emergence of private organizations focused on the manufacturing and commercialization of graphene and graphene-based materials. Forty-four companies are currently active in it, and a range of these materials have been made commercially available. Nevertheless, only a few graphene-based products have entered the market (for further details, please read the section on “General application of graphene and graphene-based composites”). Since then, many graphene manufacturing companies have sprung up all over the world, producing not only small graphene sheets but also large-area, high-quality graphene films on an industrial scale. In particular, the production industries have developed rapidly in China, USA and UK (for further details, please read the section on “Graphene industry and place for graphene in the future”). Small sheets and large-area films are the two major forms of graphene exploited for various applications. Small graphene sheets can be used in composites, functional coatings,

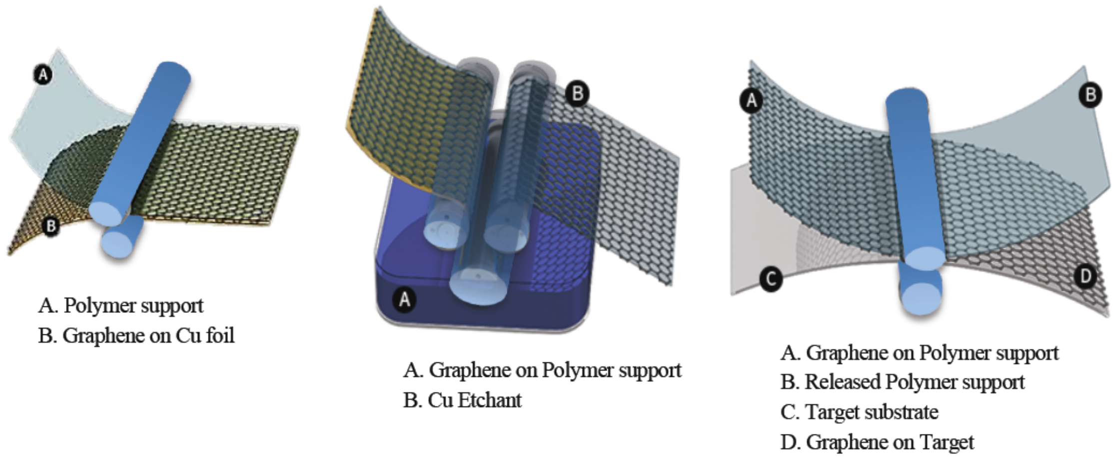


Fig. (11). Schematic of the roll-based production of graphene films grown on a copper foil. The process includes the adhesion of polymer supports, copper etching (rinsing) and dry transfer-printing on a target substrate. Wet-Chemical doping can be carried out using a set-up similar to that used for etching [76]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Table 3. Advantages and disadvantages for techniques currently used to produce graphene [58].

	Advantages	Disadvantages
Mechanical exfoliation	Low-cost and easy, No special equipment needed, SiO2 thickness is tuned for better contrast	Serendipitous, Uneven films, Labor intensive (not suitable for large-scale production)
Epitaxial growth	Most even films (of any method), Large scale area	Difficult control of morphology and adsorption energy, High-temperature process
Graphene oxide	Straight-forward up-scaling, Versatile handling of the suspension, Rapid process	Fragile stability of the colloidal dispersion, Reduction to graphene is only partial

conductive inks, batteries and super capacitors. On the other hand, large-area graphene films can be utilized as transparent electrodes in touch panels, displays and photovoltaic devices at a low cost, and more importantly, they are expected to be employed in next-generation electronics and optoelectronics such as flexible and wearable devices.

Although the largescale production of graphene materials has been realized, many issues need to be addressed to advance their industrial applications. Like any other product, the cost/performance ratio is the greatest concern for companies when determining whether graphene can be used in their products. When competing with the existing materials, the cost becomes a big hurdle. A comparison of the quality and cost of graphene products manufactured by different methods is given in Fig. (**12**) [78].

From the beginning, the high cost of graphene and materials based on it has been considered as a major barrier. Nevertheless, today, the market price of carbon-based nanomaterials such as nanotubes and graphene oxide has decreased substantially but is still prohibitive when compared with other adsorbents which are quite cheap. It is, however, important to point out that the prices have been dropping over the years, and research advancements in new and cost-effective methods of synthesis are happening due to the increase in market demand (Fig. **13**) [79].

The global graphene market is expected to witness a significant growth (see Fig. **14**) during the forecast period primarily owing to the demand from the electronic and automobile industries in the emerging economies.

According to Zion market research in 2017 [80], the graphene market is expected to grow to 32 million USD by the year 2016 and to 194 million USD by 2022. Leading players such as IBM, Dow Corning, Intel and Boeing are planning to introduce terahertz (THz) graphene processors, which can lead to the market size reaching the billion level.

A large part of the existing literature on graphene is concerned with its electrical, optical, thermal, mechanical and chemical properties. As the techniques to synthesize graphene improve, the material is increasingly being adopted in many applications, including field effect transistor (FET), capacitor, sensor, medicine, energy, industrial and household design and many more. Researchers are also exploring how graphene behaves in different experiments, how the defects and structure affect its properties, and how graphene and graphene-based nanocomposites can be used in different applications. Fig. (**15**) reveals the number of articles on different subjects that appeared in Science and Nature [81].

3. GENERAL APPLICATIONS OF GRAPHENE AND GRAPHENE-BASED COMPOSITES

3.1. The World's First Graphene-based Products

In early 2013, a company named HEAD announced its new range of graphene tennis rackets. The material was

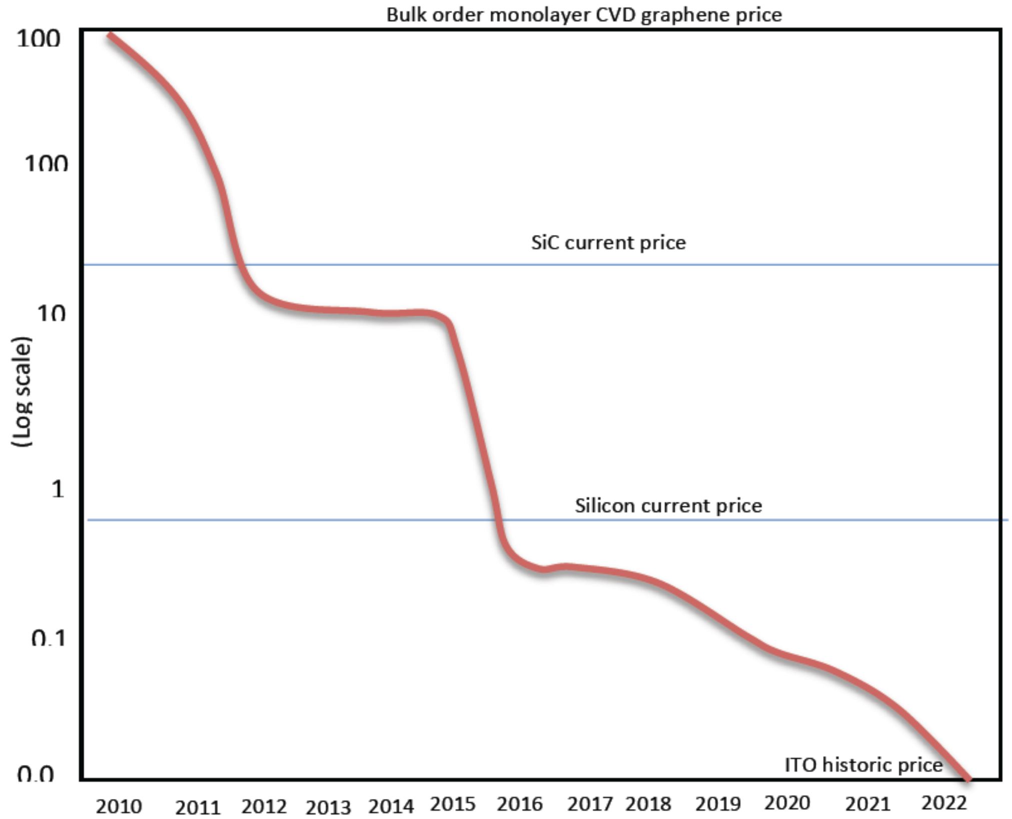


Fig. (12). Comparison of the quality and cost of graphene products manufactured by different methods [78]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

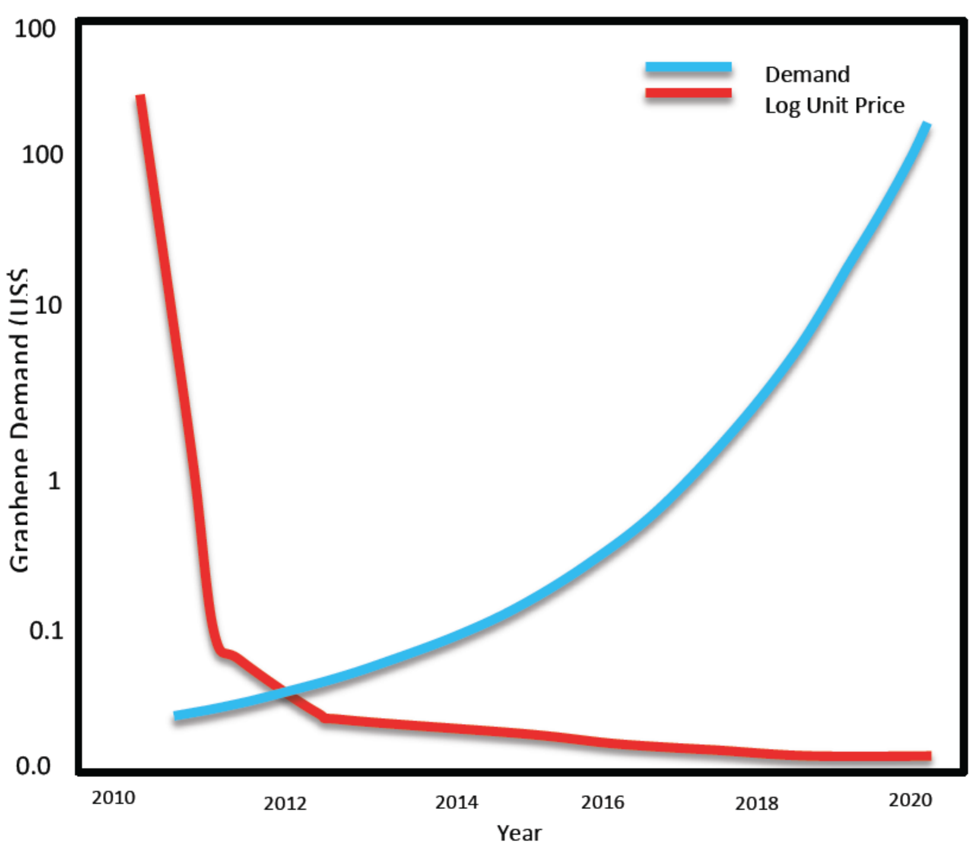


Fig. (13). Price of graphene in recent years and projected costing the future, and past and future demand. After LuxResearch, Inc., and Graphenea [79]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

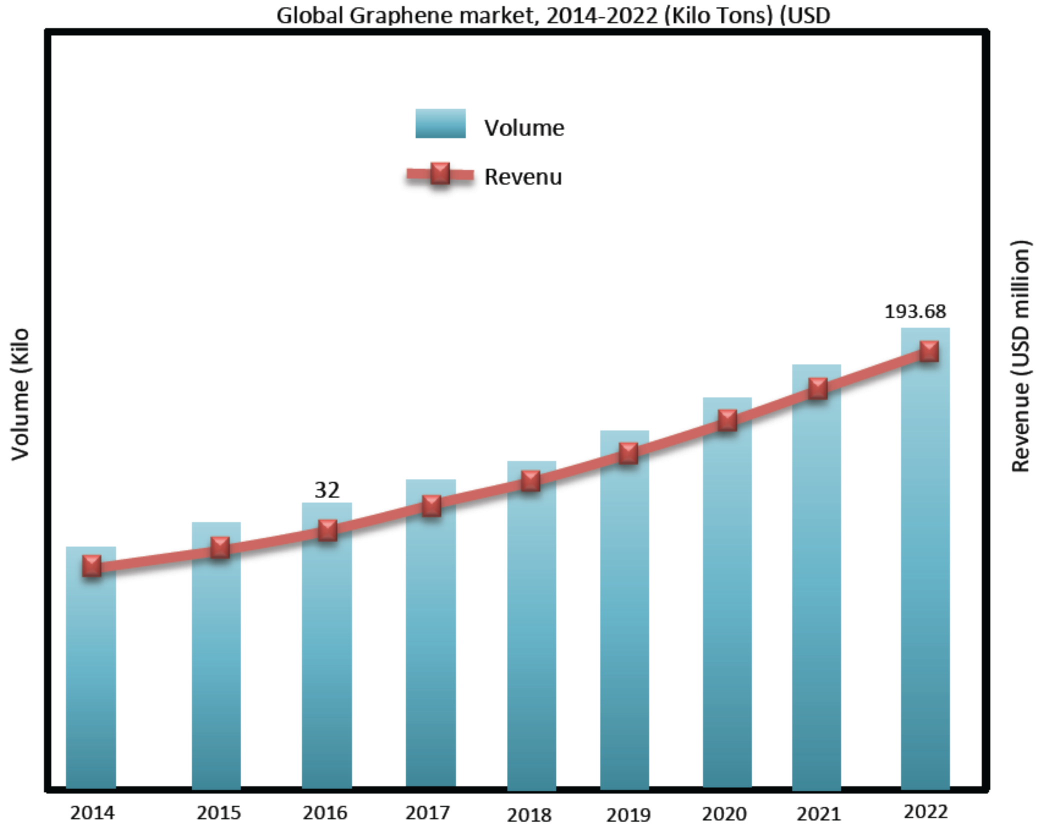


Fig. (14). Global graphene market, 2014-2022 [80]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

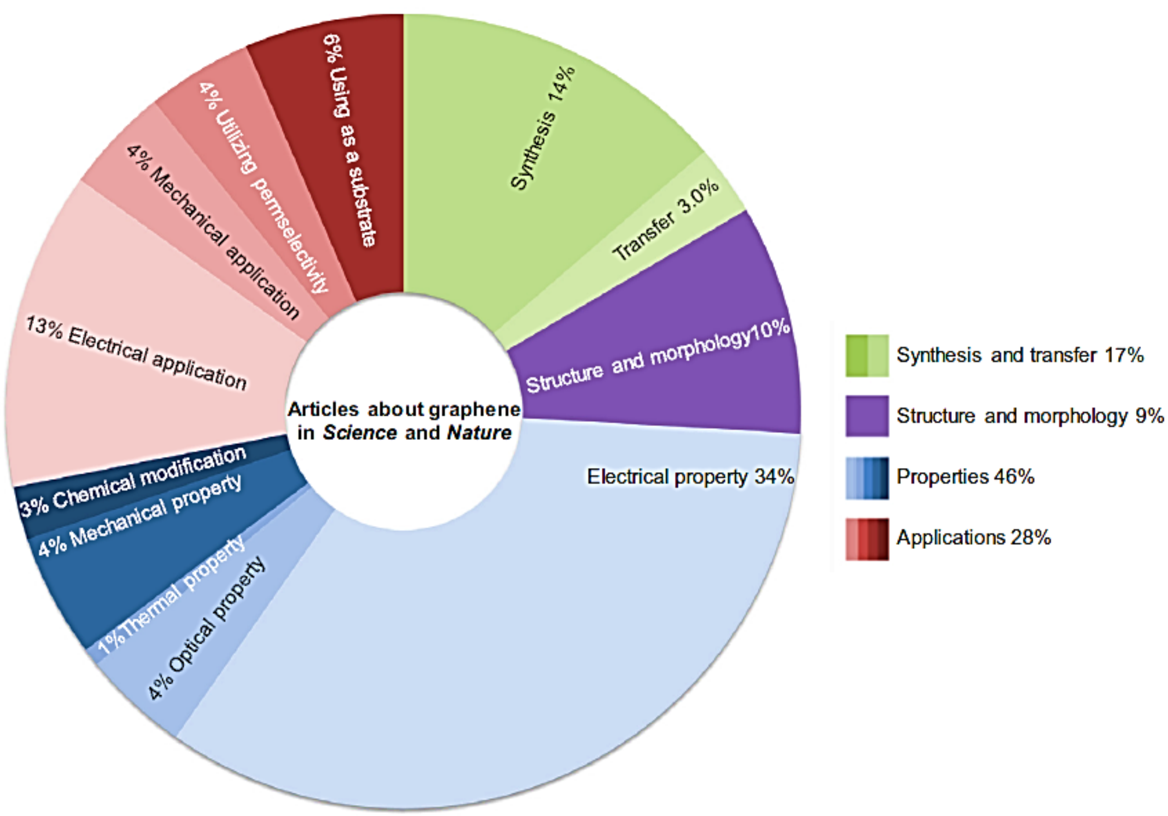


Fig. (15). Statistical proportion of graphene research articles in Science and Nature [81]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

supposedly used to make the shaft stronger and lighter, helped distribute the weight in a better way, and created a stronger and better-controlled racket [82]. On the 10th of Jan 2014, a research group from National Institute for Materials Science succeeded for the first time in making products with a structure wherein ultrathin graphene (monolayer or few layers) was glued to a 3D strutted framework [83]. On the 2nd of June 2015, researchers from G-Rods International filed a patent for their invention of a fishing rod made up of graphene, claiming that they were the first company in the world to incorporate graphene in fishing rods [84]. On the 8th of July 2016, the world's first graphene lithium-ion battery was officially released by Dongxu Optoelectronic Technology, a Beijing-based company, which greatly enhanced the battery's possible applications [85]. In July 2016, Dassi, a UK-based bike manufacturer, claimed to have designed the world's first-ever graphene-containing bike frames which weighed just 750 g unpainted but possessed the same stiffness and strength characteristics of those weighing 950 g [86]. On the 29th of November 2016, with the support of the Graphene Flagship, the Italian luxury brand Momodesign and the Italian Institute of Technology's Graphene Labs Division collaboratively launched the world's first graphene motorcycle helmet [87]. On the 17th of May 2017, "The Graphene Company" launched the world's first graphene paints in the UK [88]. In June 2017, ORA introduced the world's first graphene headphones [89]. On the 30th of August 2017, the world's first graphene boat was built as a joint innovation between Elche and Yecla. The boat was made with a mix of polymers, with graphene forming the compound in the hull [90]. In the UK, engineers at the University of Central Lancashire (UCLan) recently unveiled the world's first graphene-skinned plane in the "Futures Day" event at the Farnborough Air Show 2018 called Juno. The 11.5-feet wide unmanned airplane also boasts graphene batteries and 3D-printed parts [91]. This innovation was achieved by a unique method inspired by the blown sugar art, which can be called the "chemical blowing method". The research results were published as an achievement of the World Premier International.

Center for Materials Nanoarchitectonics (WPI-MANA) in the online version of a UK science magazine, Nature Communications, on the 16th of December 2013 [83]. On the 15th of January 2018, an academician from the University of Sunderland working on the use of graphene in the automotive industry successfully produced the world's first prototype composite component [92]. On the 7th of May 2018, a joint venture between Graphenest and Sipre (a Portuguese kayak manufacturer known for its flat water, ocean and open water kayaks) produced what is hailed as the lightest surfski kayak in the world. The product is 5.75 meters long and weighs only around 9.3 kg [93]. On the 20th of June 2018, the world's first-ever sports shoes to utilise graphene was officially unveiled by the University of Manchester and the British brand Inov-8 [94]. On the 16th of August 2018, Vollebak, an innovative clothing manufacturer, produced a graphene jacket that can conduct power, store body heat and repel bacteria [95]. In September 2018, Küschall, a Swiss-based company, in partnership with a Formula 1 manufacturer, designed the world's first and lightest wheelchair using graphene [96]. Fig. (**16**) displays the summary in a picture format, showing when each of these graphene-based materials was launched for the first time in the world. Though there have been several other first-time graphene-based products, those details have not been covered here owing to the scope limitations of the paper.

Owing to the possibility of achieving multifunctional properties in polymers by reinforcing them with graphene, several fields have started to exploit these composites. Fig. (**17**) presents the different fields where graphene-based composites are being used.

4. GRAPHENE IN THE AUTOMOTIVE AND OFF-HIGHWAY VEHICLE INDUSTRY

4.1. Automotive

One of the areas in which graphene is attracting interest is the automotive sector. Today's scientists and engineers are finding a number of ways to deliberately make materials at nanoscales to take advantage of their enhanced properties.

Toyota Motor Co. started the use of nylon-6/clay polymer nanocomposites in 1991 when it manufactured timing belt covers as a part of the engine for their newly designed Camry cars [97, 98]. At the same time, Japan developed nylon-6 polymer nanocomposites for the engine covers used in Mitsubishi vehicles [99]. General Motors (GM) had its first exterior trim application of nanocomposites in the 2002 mid-sized vans [100]. The part was stiffer, lighter and less brittle at cold temperatures and was also more recyclable. GM uses about half a million pounds of nanocomposites each year. The wide applications of clay-polymer nanocomposites in the automotive field are exhibited in Fig. (**18**) [101].

Like carbon fibre, graphene was accepted in the automotive sector. Fig. (**19**) provides an overview of the most common applications of the material in this sector [102]. In 2013, under a new project titled 'Graphene Flagship (GF)'[103], the European Commission (EC) invested €1 billion to develop graphene-related technologies from use in academic laboratories to applications in a range of industries over a period of 10 years. The GF is coordinating with 142 academic and industrial research groups in 23 countries for graphene-related research projects. According to a press release [104], one of the projects looking for EU funding was set up with the aim of developing lighter, stronger, safer and more energy-efficient vehicles using graphene to 'potentially revolutionize the global automotive industry'. The scheme was initiated by the Automotive Engineering Professor Ahmed Elmarakbi of the Department of Computing, Engineering and Technology of the University of Sunderland, England.

The GF has managed to develop a lightweight but strong graphene and fibre composite material bumper (see Fig. **20**). The small inside ribs are made of glass fibre and graphene reinforced thermoplastics [105]. The university is working with five research partners from Italy, Spain and Germany, namely Nanesa, the Centro Ricerche CRF of Fiat Chrysler Automobiles FCA (Fig. **21** shows how the Fiat researchers see numerous potential automotive applications for graphene),

Fig. (16). Summary in a picture format, showing when each of these graphene-based materials was launched for the first time in the world. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

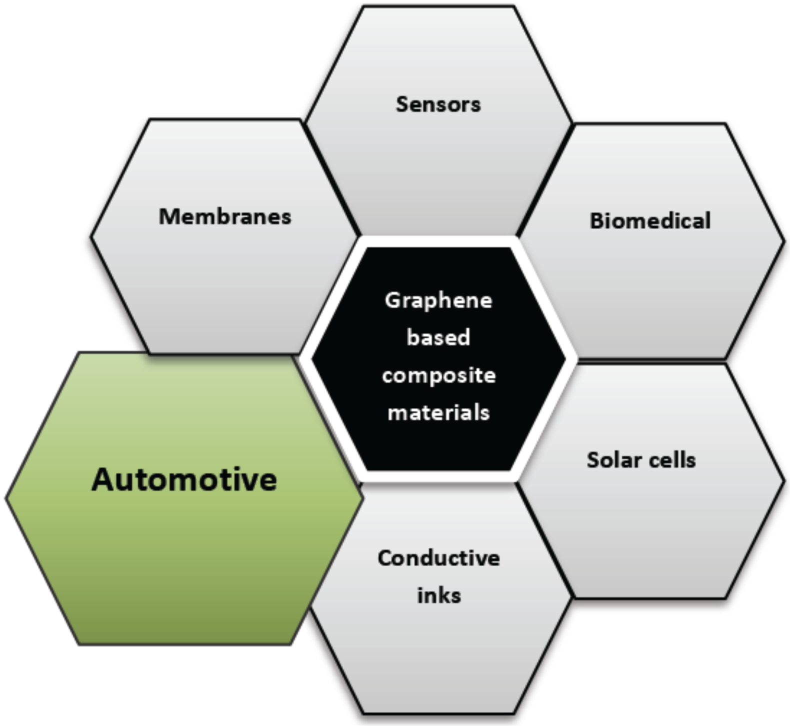


Fig. (17). Promising application areas of graphene-based composite materials. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

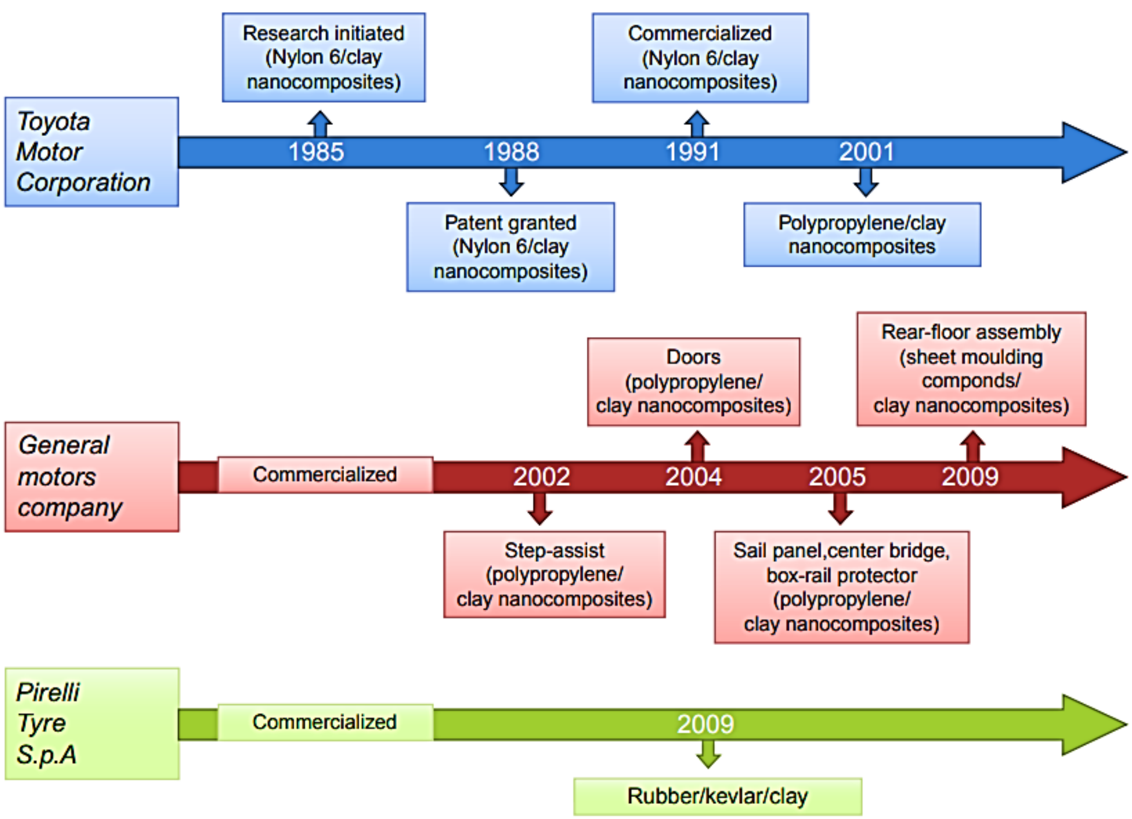


Fig. (18). potential of clay-polymer nanocomposites for automotive applications [101]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

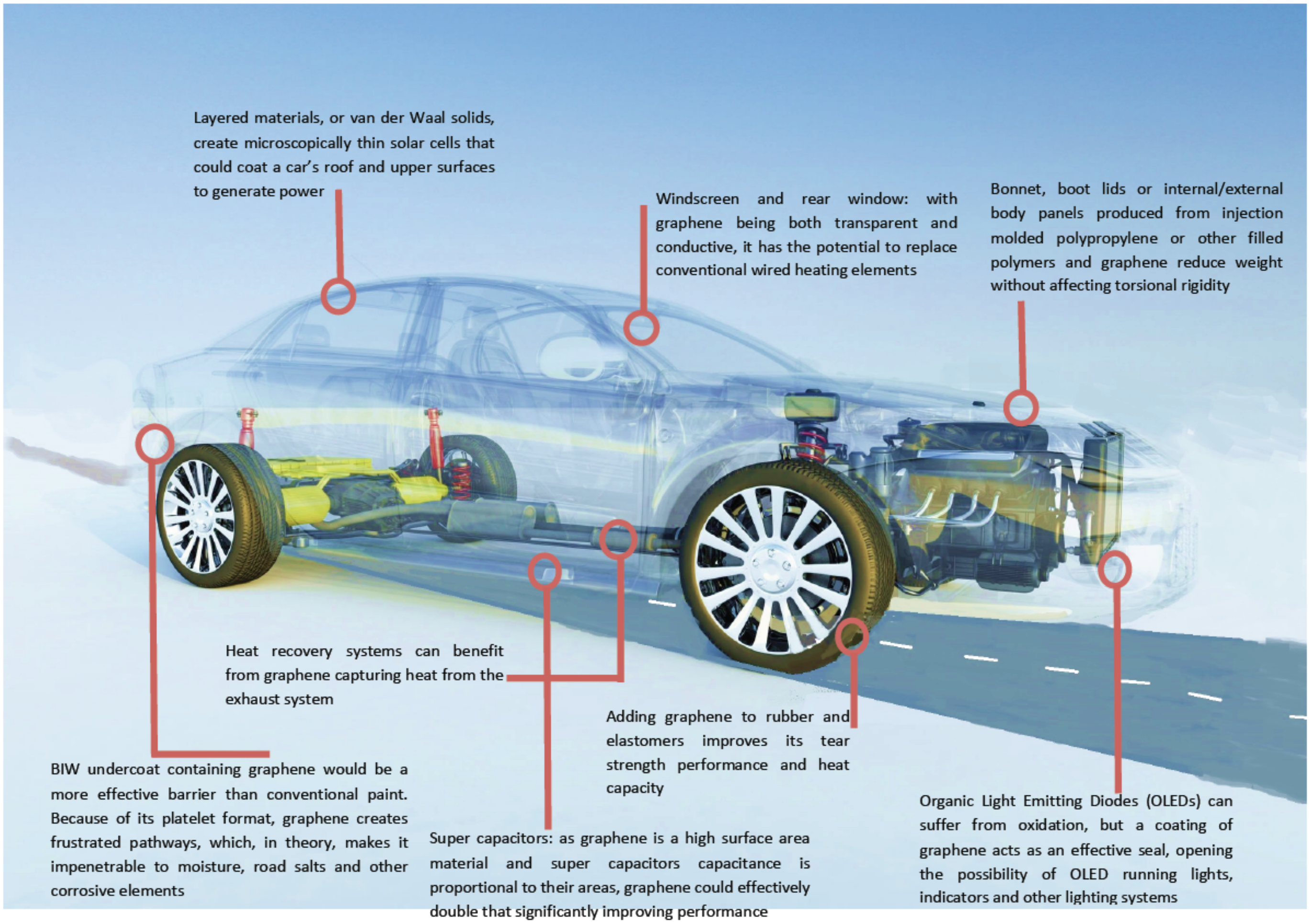


Fig. (19). Common potential applications of graphene in the automotive sector [102]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

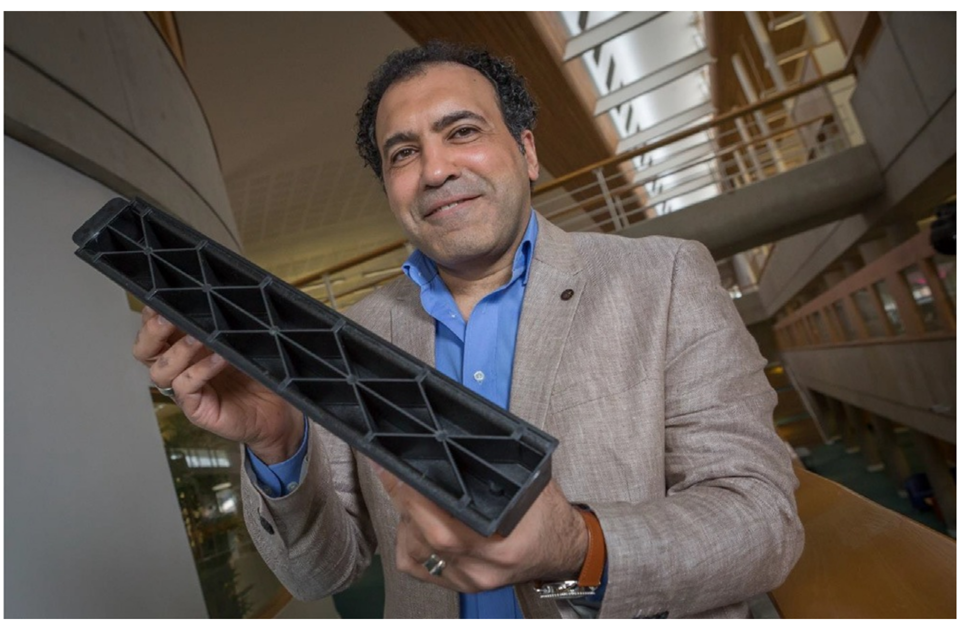


Fig. (20). Ahmed Elmarakbi with his fiber composite material bumper made of graphene [105]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

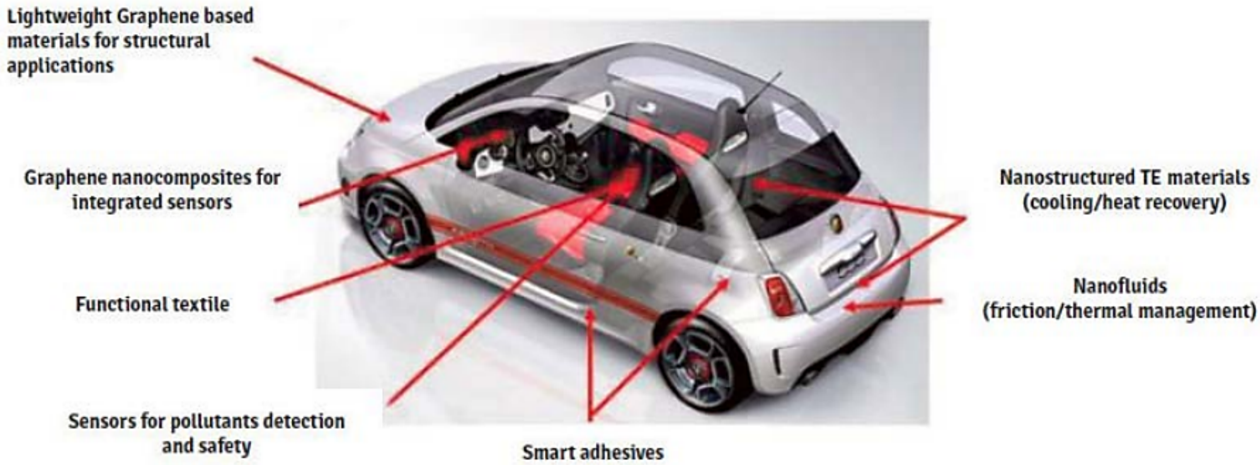


Fig. (21). FIAT researchers see numerous potential automotive applications for graphene [106]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

the Fraunhofer ICT, Interquímica and Delta-Tech S.p.A [106].

Y.M. Lin and his team demonstrated the high potential of graphene for automotive electronics applications [107]. Modern cars are equipped with a number of radar systems to cover different viewing angles as seen in Fig. (**22**). Graphene as a material platform is an attractive choice for high-frequency radar electronics because of its enormous electron mobility and its ultimately thin nature.

Cheng *et al*. [108] extracted a cut-off frequency of 427 GHz for a 67-nm channel length self-aligned graphene transistor (see Fig. **23**). Comparing the young age of graphene with the longer timescales of other devices, these results are inspiring. The findings are also a clear indication that graphene field effect transistors (GFETs) have the potential to pass the THz-border in the near future. Thus, graphene may offer a cost-efficient platform for novel applications in a variety of fields such as spectroscopy and automotive radar in analogue high-frequency electronics.

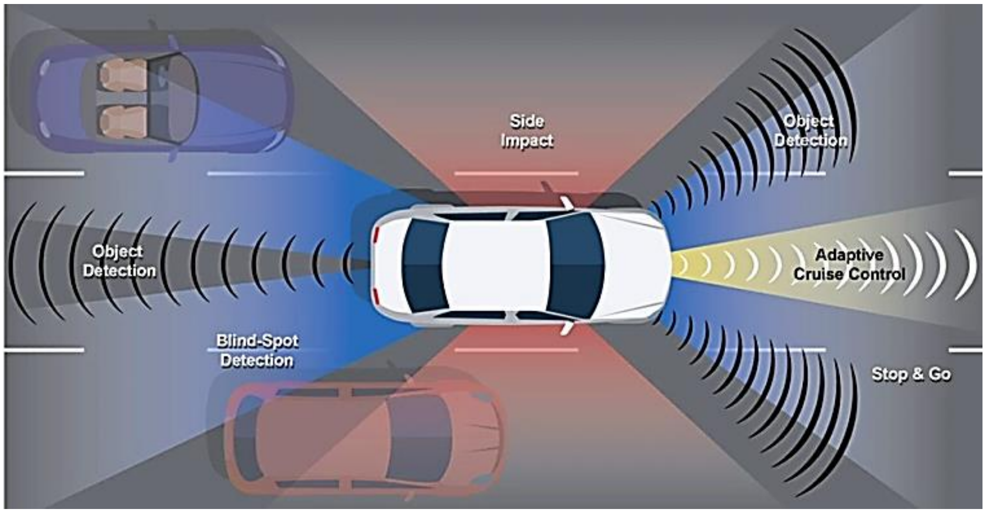
Graphene has also been used with silicon to make Si/graphene nanocomposites which are considered one of the most promising anode materials for next-generation high energy density lithium-ion battery (LIB). One of the often-quoted obstacles to the creation of the electric vehicle is the impact on infrastructure owing to the load-balancing issues with the electricity grid. If such a battery is to be used to power an electric vehicle, it will definitely go a long way in addressing certain problems as cars powered by such batteries are not likely to require charging every day. Graphene in the form of balls can also be used in EV applications to enhance fast charging and high rate operation [109]. Hyuk Son and his team [110] have demonstrated that the graphene-ball coating improves the cycle life and fast charging capability by suppressing the detrimental side reactions and providing efficient conductive pathways.

Adgero [111] unveiled the world's first operational road transport hybrid system at Britain's largest commercial vehicle show in April 2016. He partnered with the leading European manufacturer, SDC Trailers, to install their UltraBoostST system on a 13.6 m curt insider trailer finished in the livery of a major UK-based transport and distribution company, Eddie Stobart. During braking, the unit becomes a generator, recovering kinetic energy that would otherwise be lost as heat. This vehicle is equipped with five high-power graphene-based ultra-capacitors which recover kinetic energy during braking. The hybrid solution is estimated to reduce fuel consumption and associated emissions by up to 15-30%.

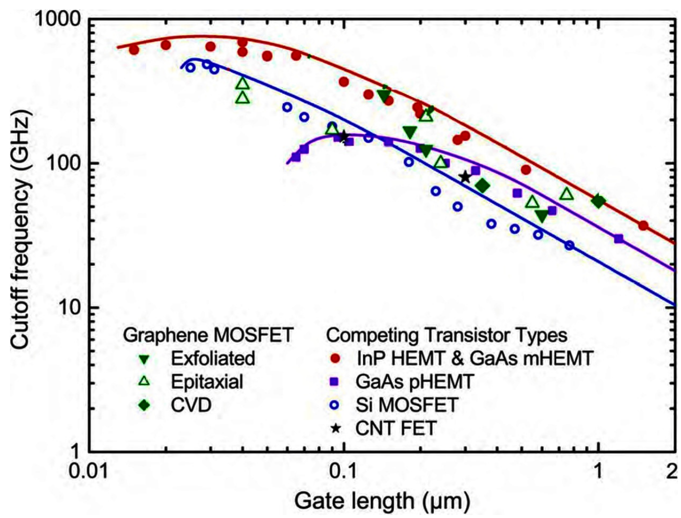
Since the high electrical conductivity and optical transparency of graphene make it a beneficial material in the configuration of user interfaces, touchscreens and liquid-crystal displays (LCDs) are often used in different applications. Such interfaces are now finding their way into the dashboards of many vehicles where the user interface presented to the driver is becoming just as important as the performance of the vehicle [112]. Another exceptional property of graphene, its flexibility, has been shown to have application in making screens which can fit over curved surfaces. This means that the entire vehicle can become a space for viewing content without the traditional constraints associated with the shape of the dashboard. Fig. (**24**) portrays how researchers view the potential applications of graphene in the automotive industry, especially the graphene-based dashboard and touchscreens.

Lubricants (see Fig. **25**) reduce friction between the contacting surfaces and thus increase the energy efficiency of engines and other machines. These substances can also reduce wear, thereby extending the life of tribological components. "Every year, millions of tons of fuel are wasted because of friction," said Jiaxing Huang, associate professor of materials science and engineering at Northwestern University's McCormick School of Engineering [113]. Jiaxing Huang claims that graphene balls can improve the oil's lubricant performance in an engine and transmission.

Subsequently, his team planned to explore the additional benefits of using crumpled graphene balls in oil and discovered that they can also be used as carriers. Because the ball-like particles have the high surface area and open spaces,



(**a**)



(**b**)

Fig. (22). (**a**) Radar systems in modern cars (**b**) Potential of graphene for automotive electronics applications [107]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

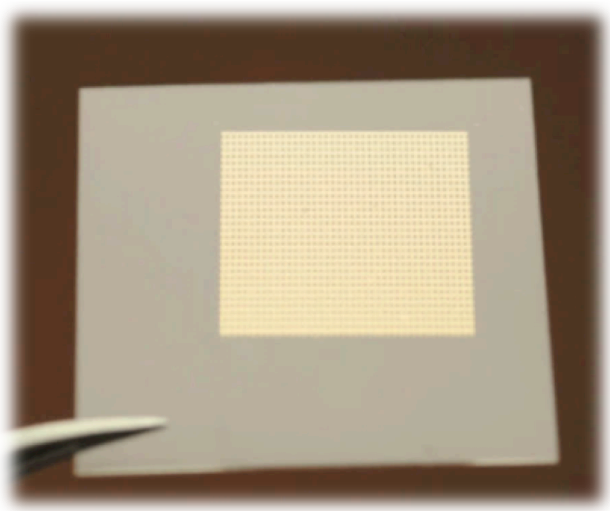


Fig. (23). The self-aligned graphene transistor [108]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Fig. (24). Graphene-based dashboard and touchscreens [112]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Fig. (25). Automotive lubricants. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

they act as good carriers for materials along with performing other functions such as corrosion inhibition as shown in Fig. (**26**) [114].

A practical application of graphene as a grease additive was presented by Andrea Mura and his team of Politecnico di Torino in 2018. In particular, grease added to graphene nanoplatelets has been evaluated as an enhanced performance lubricant for spline couplings as indicated in Fig. (**27**) [115, 116].

With the progress made in nanotechnology, engineers and researchers are in the process of improving the thermal efficiency of radiators through the application of nanoparticles. Recently, the effect of graphene nanoplatelets nanoparticle suspension on the thermal performance of automotive radiator (as shown in Fig. **28**) was investigated by Leslie Kok Lik Toh of University College of Technology Sarawak [25]. The study revealed that the Nusselt number enhances as the volumetric concentration and the Reynold number increase. This improvement could elevate the performance of an automotive cooling system, leading to a smaller radiator and decreased fuel consumption by the engine. The researcher also found that the presence of nanoparticles can significantly augment the radiator's heat transfer rate in a manner dependent on the quantity of nanoparticles added to the base fluid.

The UK-based company Linney Tuning is using bi-layer graphene in the development of brake pads (as shown in Fig. **29**), and the technique is currently in the development/testing stage. They claim that the addition of graphene as an automotive friction ingredient can yield greater wear resistance than the conventional car brake friction material and also provide a high friction coefficient to increase the long-term durability, making it possible to assuage the noise problem during braking [117, 118].

Applied Graphene Materials (AGM) has worked with Magna Exteriors and prepreg specialist SHD Composites to help develop a Fenyr SuperSport tailgate [119, 120] for W Motors (see Fig. **30**). They are subsequently developing the MTC9810 epoxy prepreg system.

A car made of graphene would be the very definition of blue sky thinking. But this should not stop graphene from being used to construct various vehicle features [112]. The world's first graphene car, the BAC Mono (as shown in Fig. **31**), was unveiled in Manchester in 2016 and received

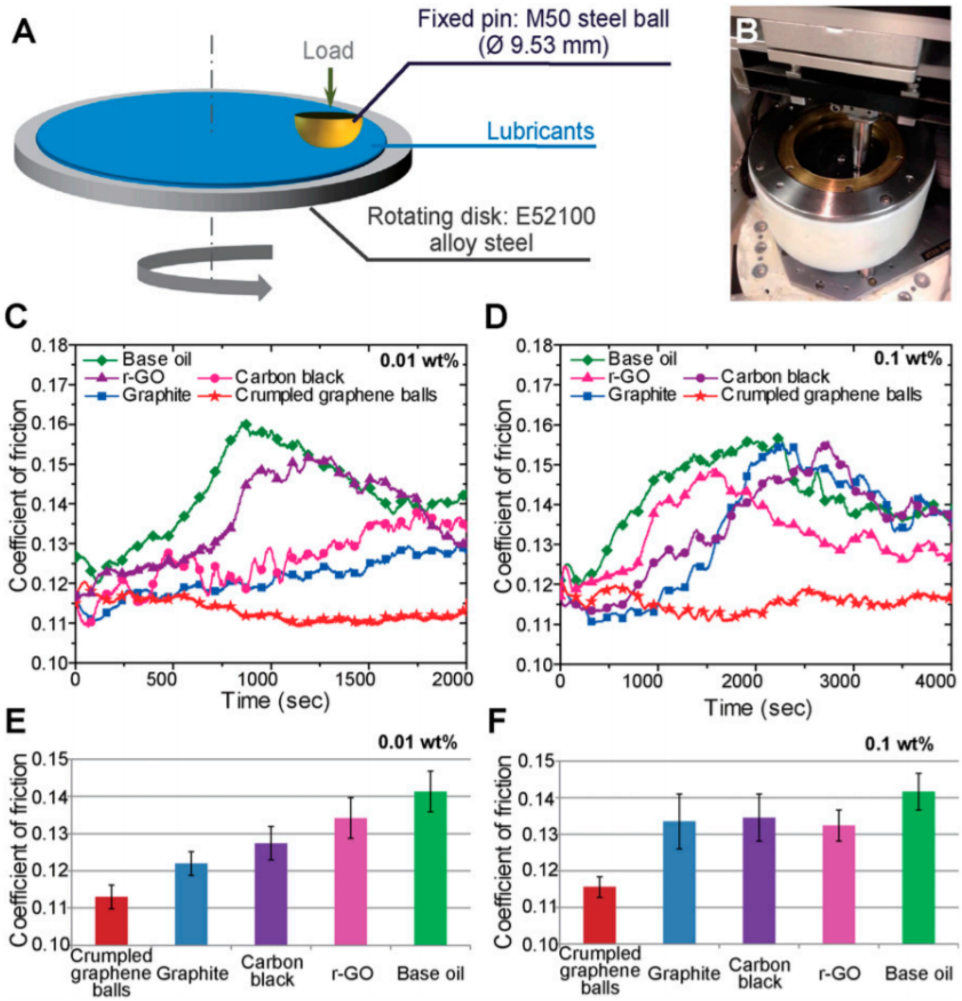
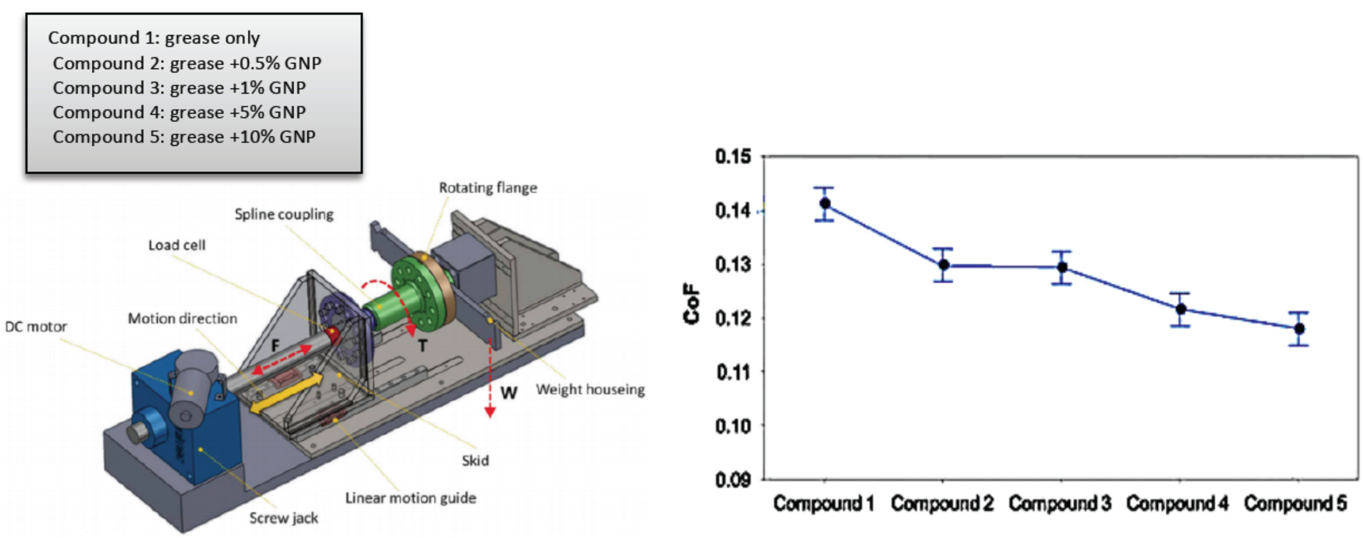


Fig. (26). Test performance comparisons of crumpled graphene balls in oil with other lubricant materials (**a-b**) test set-up (**c-f**) results [114]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).



(**a**) (**b**)

Fig. (27). (**a**) Test rig schematic (**b**) Plot of coefficient of friction (CoF) *vs.* Graphene nano platelets (GNP) percentage with 95% Confidence Intervals [115]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

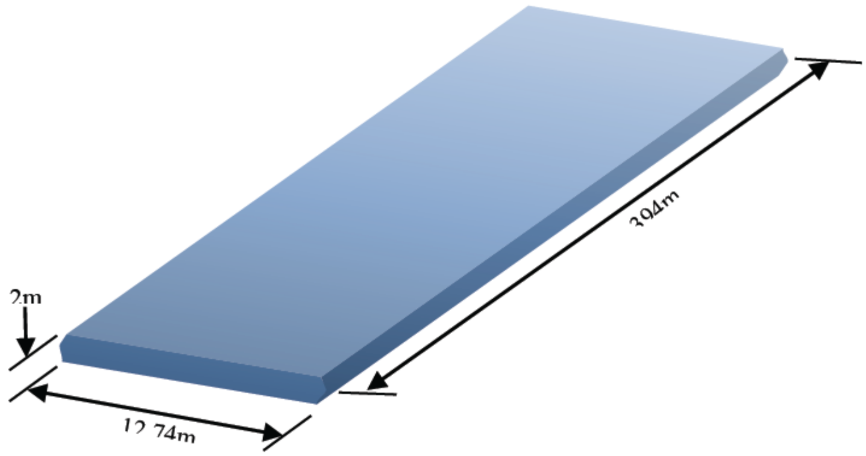


Fig. (28). Dimensions of the flat tube automotive radiator [25]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Fig. (29). Graphene brake pads Linney Tuning, a UK-based company [117]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Fig. (30). W Motors Fenyr SuperSport tailgate using AGM's graphene-improved epoxy prepreg [119, 120]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

immense attention from the academics, scientists and industrial experts when the Duke and Duchess of Cambridge sat in the driver's seat during a visit to Manchester [121].

Furthermore, in 2017, a research team from the University of Alabama successfully fabricated a light Chevrolet Camaro car hood using graphene [122] as shown in Fig. (**32**).

In 2014, FORD motor company began working jointly with Eagle Industries and XG Sciences to study the material behaviour of graphene and its usage in running trials with auto parts such as fuel rail covers, pump covers and front engine covers made of the material [123]. Finally, in press news dated October 9, 2018 [124], Ford Motor Co. announced that it intends to use graphene nanomaterials to

Fig. (31). The world's first graphene car, the BAC Mono, was unveiled in Manchester in 2016 [121]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Fig. (32). Lighter Chevrolet Camaro car hood using graphene [122]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Fig. (33). Mustang of FORD [125]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

enhance the foaming for noise reduction inside its vehicles and increase the performance under the hood. They realized that graphene mixed with foam constituents resulted in 17% reduction in noise, 20% improvement in mechanical properties, and a 30% augmentation in heat endurance when compared with the foam without the material. Graphene is expected to go into production by the year-end 2018 for over 10 underhood components in the Ford F-150 and Mustang (see Fig. **33**) and eventually other Ford vehicles as well [125].

As per the press news dated October 18, 2018, Nissan unveiled the progressive design of the most awaited SUV in India [126]. The body is designed and built with a graphene structure that has the inherent capability to absorb impact energy, making the New Nissan KICKS stronger, safer and more durable on the Indian roads as shown in Fig. (**34**).

The use of graphene in next-generation lithium-ion batteries is currently being widely studied. Quite recently, the Australian advanced materials technology company, Talga

Fig. (34). Kicks of NISSAN [126]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Fig. (35). 3D printed graphene based vehicle of Local Motors [130]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Fig. (36). Demonstration of graphene-modified lubricant in the wheel loader of LiuGong machinery corporation [131]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Resources Ltd., signed a letter of intent (LOI) with Schunk Carbon Technology GmbH, a subsidiary of the German-based Schunk Group. Under the LOI, Talga and Schunk will cooperate on the exploration and incorporation of Talga graphene (Talphene®) into a Schunk product with applications in the automotive sector [127]. Advanced materials producer First Graphene presented the latest data, proving the quality of its PureGRAPH™ range at the Graphene Automotive 2019 held in March. PureGRAPH™ is a low-defect, high aspect ratio graphene product with low metal and silicon contamination levels and is targeted for the car industry [128].

With the advancements in nanotechnology, graphene will revolutionize the 3D printing industry, and consequently other industries too. The industry needs to understand the reality of the issues in implementing such a printing considering the fact that it is challenging to make something out of graphene in large quantities [129]. It is too expensive to make a printable structure of graphene material with a 3D printer on an industrial scale. Besides, it also challenging to create a 3D printed graphene shape which is bigger than the size of a credit card. US-based Local Motors (see Fig. **35**) plans to 3D print vehicles within 12 hours [130] by reinforcing extruded printed materials with graphene. The company is discussing with a Korean firm about sourcing graphene for extruding in composite 3D printing materials.

4.2. Off-highway Vehicle Industry

LiuGong Machinery Corp. announced in July 2018 that it has established the technical standards development and application demonstration base of graphene-modified lubricant at its Global R&D Center in Liuzhou, China [131] (see Fig. **36**). "Studies have found that graphene can significantly improve the anti-wear and anti-friction performance of lubricating oil under extreme pressure, reduce fricative wear and noise of a machine, so it can improve the reliability of con-

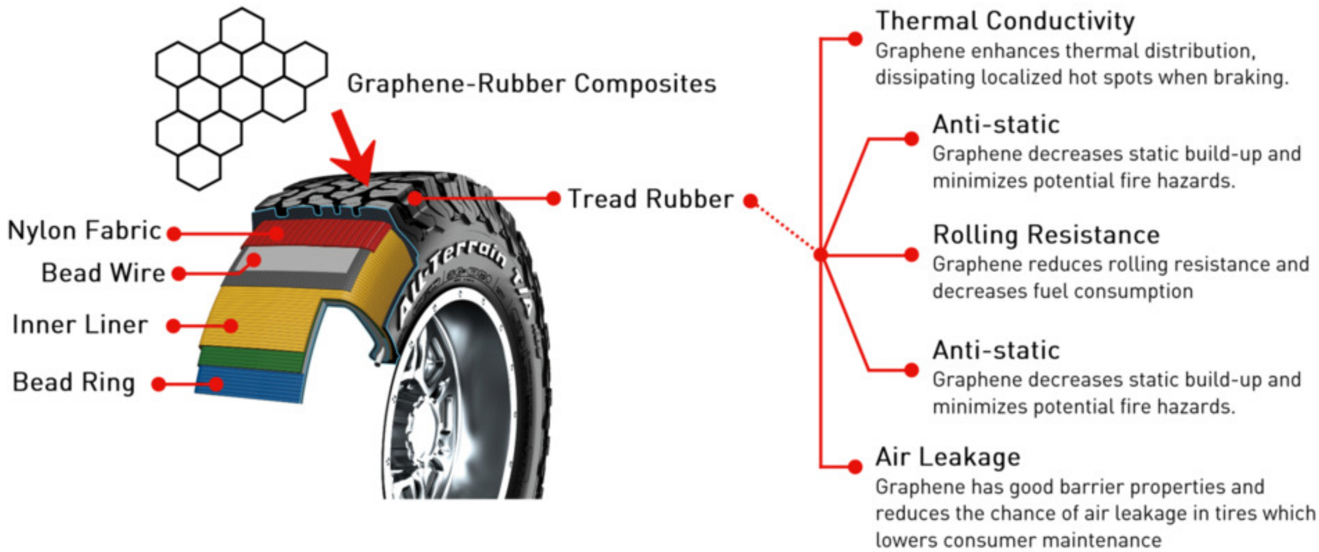


Fig. (37). A schematic of tyre using graphene -rubber composites [117, 132]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

struction machinery and the lifetime of components," explains Abby Lin, Deputy Director of New Tech R&D at LiuGong.

The company has fully considered machine designs and requirements while developing graphene-modified lubricants. Hence, it would not be necessary to make any changes to the existing equipment, components or systems to use them. LiuGong has plans to complete the formulation development of the lubricants within two years and massive applications and sales within a period of five years. The company intends to subject the lubricants to various bench, reliability and field tests under different working conditions.

Tire compounds is another area in which the use of graphene is making headway, and this includes the heavy equipment industry. Among the many graphene-based products, Global Graphene Group (G^3) [117, 132] offers graphene-enhanced rubber composites for tires as shown in Fig. (**37**). The company claims that graphene-enhanced rubber offers key performance improvements such as enhanced thermal conductivity, gas barrier properties, mechanical strength and wear resistance. While rubber itself is an insulating material, it does not dissipate heat well. However, graphene's 2D structure enables it to form an overlapping network within the rubber to increase the tortuous path for gas diffusion, further reducing the chances of air leaks in the tires.

Qingdao Sentury Tire, a Chinese tire company, and Huagao Graphene Technology, a graphene producer in the country, have signed an agreement to produce "electrostatic tires" [133] as shown in Fig. (**38**). The firms have reportedly started the trial production of graphene-based conducting tires in October 2015 and have now agreed to launch mass production. According to the plan, the output will be 5 million tires a year in the first five years, and the amount is set to double over the second five-year period. Other firms using graphene in tires are Shangdong Hengyu Technology [134] and Vitorria [135].

Fig. (38). A schematic of tyre using graphene - by Qingdao Sentury Tire. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Manoeuvring off-highway vehicles in the building sites is dangerous for the people working nearby. The large dimensions and design of the off-highway vehicles cause many blind zones for the machine operators that complicate the driving task [136]. For reducing the number of accidents, a collision warning system must be designed and implemented. To cover the whole perimeter of the off-highway vehicles, several sensors that work jointly will be required. Furthermore, sensor redundancy will help to reduce the number of false alarms. Graphene as a material platform is an attractive choice for these high-frequency radar electronics applications [137] in the off-highway vehicles as shown in Fig. (**39**).

Adding graphene to asphalt improves the durability and sustainability of the road surfaces [138], making the asphalt less likely to soften in warm temperatures or harden and crack in cold conditions. The additive also reduces road wear, particularly under high loads, by increasing the elasticity and strength of the asphalt.

Fig. (39). High-frequency radar electronics application in the off-highway vehicles [136]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

As written in the article "World Highways" issue dated September 2018 [139], a new material system has been developed jointly by Guangxi University and Guangxi Zhenglu Machinery Technology to improve the sustainability of asphalt road surfaces as shown in Fig. (**40**). This is said to be a key technical breakthrough for road surface materials and is claimed to solve the common problem of short surface-longevity seen in the highways. Another important factor is that this technology is highly cost-efficient, thus delivering economic benefits.

5. MODELLING AND SIMULATION

Graphene is usually studied as a two-dimensional structure because of its nanoscale thickness. For understanding its mechanical properties, several attempts, such as experimental measurements, theoretical developments and numerical modelling, have been made. Nonetheless, the integrations between these techniques is still not clear [29] for some high-performance structural applications.

Various theoretical and computational approaches have been employed to explore the reinforcement effect of graphene on the performance of polymer nanocomposites including but not limited to quantum mechanics (QM) and continuum mechanics (CM) [140], molecular mechanics (MM) [141], molecular dynamics (MD) [142], tight binding molecular dynamics (TBMD) [143, 144], atomistic modelling [145, 146], density functional theory (DFT) [147, 148] and multiscale modelling [149, 150]. Investigators routinely use two main approaches when modelling graphene composites. The first approach focuses on the molecular level interactions while the second one is continuum modelling which considers the overall deformations. The latter includes the Mori-Tanaka model, rule of mixtures and the Halpin-Tsai model. Multi-scale models, which combine the molecular and continuum models, have also been developed.

For example, Ahmed Elmarakbi *et al*. [151] investigated the non-linear elastic moduli of graphene sheet-reinforced polymer composites using a combined molecular mechanics theory and continuum homogenisation tools. They also endeavoured to derive the effective response of the composite based on the modified expression for both Eshelby's tensor and Mori-Tanaka schemes. Their recently-developed procedure [29] for the multiscale modelling of graphene-based polymer composites to enable automotive light-weighting and crashworthiness is depicted in Fig. (**41**) [29].

Recently, Deji Akinwande *et al*. [152] published a review article covering most of the theoretical investigations focusing on the interacting mechanisms, physical properties and potential applications of graphene and graphene-based composites. Furthermore, Guo *et al*. [153] proposed a 3D

Fig. (40). The Nanning Bridge- graphene bsed asphalt road surface [139]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

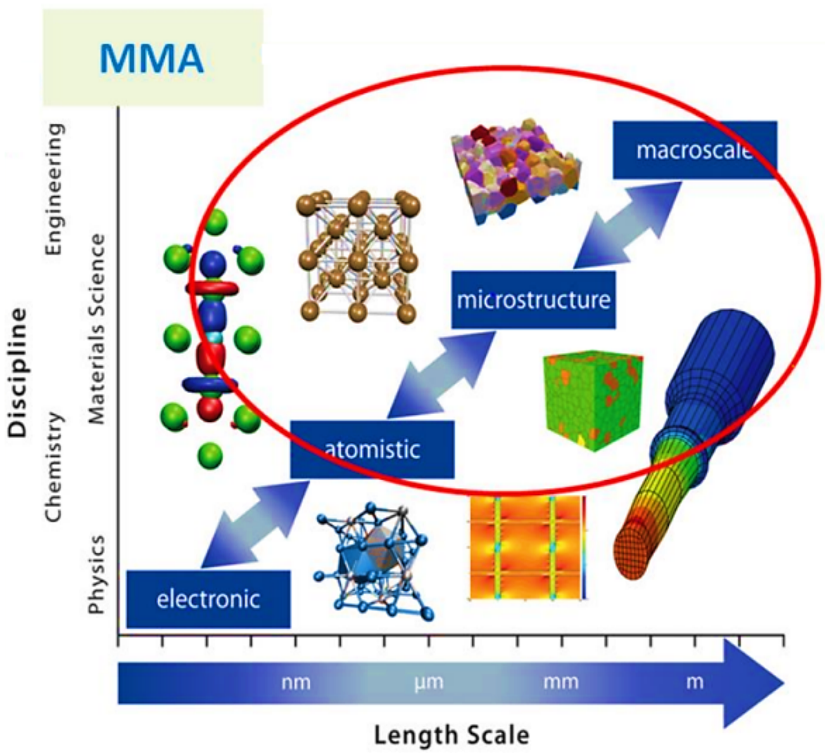


Fig. (41). The multiscale modelling approach (MMA) [29]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

multiscale simulation method based on ABAQUS finite element software for analysing the mechanical behaviour characteristics of the graphene-reinforced polymer-matrix composites. The concept of the representative volume element (RVE) was applied by Guo *et al*. [153] to study the composites at the nanoscale. The RVE consists of three parts, namely single-layer graphene, matrix material and graphene/matrix interface (see Fig. **42**) [153].

Besides, nanoscale modelling software can become an important factor in the next few years, saving a lot of money or experimentation for the various vehicle manufacturing companies. Many of them are currently in discussion with different software developers to make this technology commercially available. For instance, Associate Professor Alexander V. Kildishev [154] at Purdue University's Birck Nanotechnology Center is at the forefront of graphene research. Among his many works are graphene devices that are designed in COMSOL Multiphysics and then fabricated and tested experimentally. Pavol Lengvarský *et al*. [155] applied ANSYS to predict Young's modulus of graphene sheets by

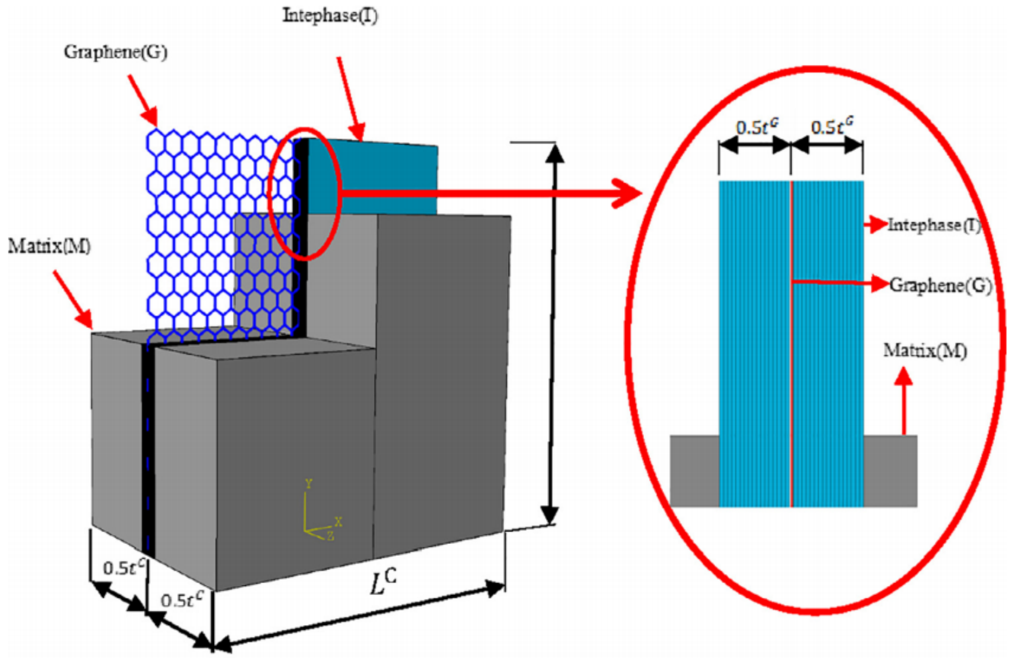


Fig. (42). The RVE of graphene-reinforced composites and the model of the interface [153]. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Table 4. Companies provide software and other technologies for grapheme.

Sl. No.	Companies	Products
1	FEKO	Provides software solutions
2	Materials Studio	Provides software solutions
3	FETD engine	Provides software solutions
4	Atomistix ToolKit and Virtual NanoLab	Provides software solutions
5	Exabyte.io	
6	QuantumWise	Provides software solutions for development of nanotechnology. The company is working in close collaboration with the Nano-Science Center at the Niels Bohr Institute of Copenhagen University
7	Ascalaph Designer	Molecular modelling
8	ConNTub	Cheminformatics and Molecular modeling
9	COMSOL	Provides software solutions
10	QuantumATK	Solutions for material modelling
11	TCAD	Technology computer-aided design software
12	Ninithi	Opensource modeling software
13	ANSYS	Provides software solutions

the finite element method in which graphene sheet is modelled as a space frame structure by using beam elements. SAMSON school claims that SAMSON is a novel software platform for computational nanoscience and it can rapidly build models of nanotubes, proteins, and complex nanosystems [156]. Graphene-related companies that provide software and other technologies are displayed in Table **4**.

6. GRAPHENE INDUSTRY AND PLACE FOR GRAPHENE IN THE FUTURE

Graphene appears to be the material of the future and promises to improve our lives. Worldwide, there are more than 200 companies that claim to produce graphene-based products and new ones are entering the sector every day. Shinohara *et al*. and Guan Gong [157, 158] categorized some of the leading graphene producers, including their key technologies and main products that are promising for various applications.

Other leading country-wise graphene producers based on information from the graphene council [159] are represented in Table **5**, and the same data in percentage is illustrated in the graphical form in Fig. (**43**).

Table 5. Companies produce graphene worldwide.

China	2D Carbon Tech Inc. Ltd. Chengdu - Timesnano Deyang Graphene Science and Technology (Carbonene) DFJ Nanotechnologies Co. Ltd Nanjing XFNANO Materials Tech Co.,Ltd - XFNANO Beijing Xin Carbon Technology Co. The Sixth Element Yurui(Shanghai)Chemical Co.,Ltd Shanghai SIMBATT Energy Technology Co., Ltd. Suzhou Graphene Nanotechnology Co., Ltd Yantai Sinagraphene.LTD
USA	DDH Advanced Materials Inc. ACS Material Angstron Materials Asbury Carbons Carbon Solutions CELTIG Graphene 3d Lab Graphene Frontiers Graphene Laboratories Graphene Supermarket - Graphene Laboratories Noble 3D Printers Nanostructured & Amorphous Materials, Inc. Cabot Garmor Inc. Graphene Technologies Graphenea Nanospan GROLLTEX XG Sciences Vorbeck Materials Reade Advanced Materials Stanford Advanced Materials Vulvox Nanobiotechnology Corporation Xolve
UK	2D-Tech Advanced Material Development Applied Graphene Materials BGT Materials Cambridge Graphene Platform Cambridge Nanosystems DGS - Durham Graphene Research Haydale Green Graphene Gwent Electronic Materials Ltd. Graphene Industries Graphenelab Ltd. Versarien William Blythe Ltd. Oxford Advanced Surfaces (OAS) Perpetuus Carbon Technologies
Spain	Applynano Nanoinnova Graphenano Graphendis Graphene Tech Gnanomat Avanzare Graphenea
Norway	Abalonyx Norwegian Graphite CealTech CrayoNano
India	Ad-Nanotech Avansa Technology & Services Log 9 Materials Nanospan United Nanotech Innovations Private Limited
Sweden	Graphensic
Canada	Elcora Resources Grafoid Graphene Leaders Canada NanoIntegris Nanoxplore Inc. Kennedy Labs
Poland	Advanced Graphene Products Sp. z o.o. Nano Carbon
Germany	AMO GmbH Future Carbon Graphenelab Ltd. Helmholtz Zentrum
The Netherlands	Applied Nanolayers Graphendo HQ Graphene
Iran	API Technology Pioneers
Malaysia	Graphene NanoChem
Italy	BEDimensional Directa Plus GNext
Finland	Canatu Ltd.
Turkey	Grafen Chemical Industries Co. Nanografen Nanografi
Thailand	Innophene Co.
Australia	First Graphene Talga Resources
Greece	Glonatech
Korea	Carbon Nanomaterial Technology Co. Ltd. Graphene Square Inc.
Japan	Incubation Alliance Kaneka InALA - Incubation Alliance
Scotland	RD Graphene
Sri Lanka	RS Mines

(Table 5) contd…

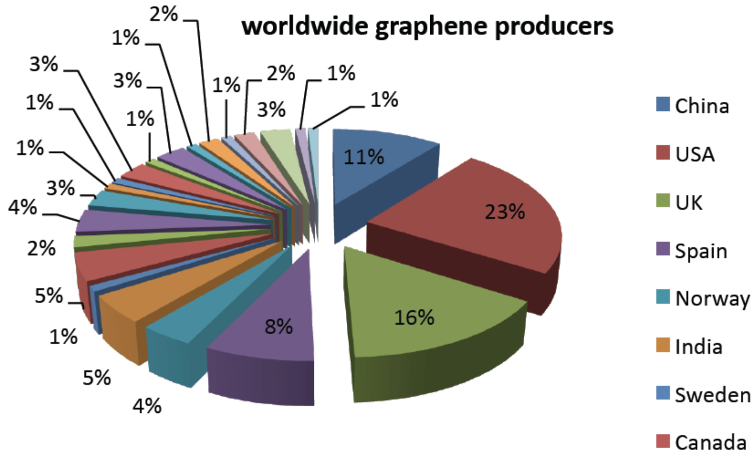


Fig. (43). Graphene producers worldwide. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

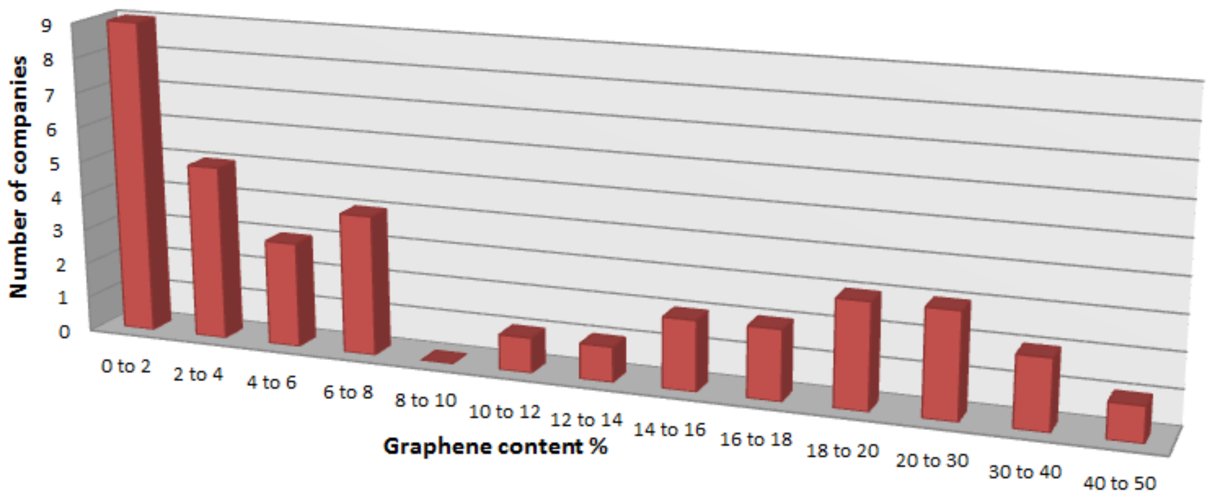


Fig. (44). Graphene content per number of companies. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

It is evident from Fig. (**44**), which is based on an earlier study [160], that the majority of the companies are producing less than 10% graphene content and no industry is currently producing it above 50%. These figures help us to understand why graphene applications are not yet popular. In terms of material properties, graphene and graphite are very different and cannot be interchanged in many important applications such as coatings, composites and batteries.

Besides, there is almost no high-quality graphene, as defined by ISO, in the market yet [160]. The lack of a properly characterized, high-quality material has been delaying the development of applications that depend fundamentally on graphene. This is not surprising given that graphene is a nanomaterial, and its characterization depends on nanotechnology tools that are not readily available or are too expensive for ordinary producers and developers.

CONCLUSION

Undeniably, graphene is now considered as the most attractive material in the world of nanotechnology and it is expected that by the year 2020 the graphene market will rise by a CAGR of 60% [161]. Owing to its outstanding properties, the material has the potential to revolutionize a wide range of applications such as engineering (nanocomposites), electronics (smart phones, transistors and ultracapacitors), medicine, energy (batteries), industrial and household design and many more fields. Graphene has hence attracted the attention of engineers and scientists across the world. The growing usage of graphene is replacing the current technologies and is opening up new markets for more applications. For example, integration of graphene into FRP composites is a highly promising way to achieve advanced composites with lighter weight, higher performance and more functionalities than the traditional FRP composites. However, to attain the full potential of the material, high-quality graphene should be produced economically and on a large scale through environmentally-friendly synthesis techniques.

The lightweight nature of material becomes an important issue for energy efficiency in the automotive and off-highway machinery industry since these vehicle markets have stringent legislation focused on controlling CO_2 and exhaust gas emissions such as particulates and NOx. Therefore, there is a need to develop a novel generation of materials that combine both weight reduction and safety issues.

In this work, the concept of conventional composites was investigated, the benefits and drawbacks were explored, and the applicability of traditional materials, as well as graphene-based polymer composites in the engineering field, were discussed. Subsequently, the available literature on graphene-based composites and their applications particularly in the automotive and off-highway industry were examined. Finally, the various mechanisms of integrating graphene as polymer reinforcements within composite materials and their related modelling, designing and manufacturing capabilities suitable for the automotive and off-highway machinery industry were probed.

Another exciting opportunity that is directly related to graphene-based polymer composite materials is the recent advances in additive or 3D manufacturing and other novel methods. These developments can lead to numerous insights and practical applications in the context of material design.

CONSENT FOR PUBLICATION

The author confirms that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere. The author authorizes Bentham Science Publishers to publish the article entitled "Recent advances in graphene-based nanocomposites for automotive and off-highway vehicle applications".

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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