Chapter

Advanced Carbon Materials for Sustainable and Emerging Applications

Aneeqa Bashir, Azka Mehvish and Maria Khalil

Abstract

Advanced carbon nanomaterials, which comprises fullerene, graphene, and carbon nanotubes (CNTs) are considered as backbone of engineering and scientific Innovation due to their versatile chemical, physical and electrical properties. Sustainable carbon materials are fabricated using different physical and chemical methods, respectively. Moreover, fabrication methods are used to achieve advanced carbon monoliths which are constituents with desirable properties. Keeping a view of desirable monoliths, diverse allotropes of advanced carbon nanomaterials are mostly employed in renewable energy resources, organic photovoltaic, and energy conservation technology, respectively. Carbon nanomaterials offer tremendous potential for enhancing biology and drug delivery because of biocompatibility. The proposed chapter grants a variety of fabrications methods for sustainable carbon materials as well as highlights the miscellaneous applications. Further, graphene, carbon nanotube (CNT) and fullerene are considered as fast and effective nanocarriers for delivering therapeutic molecules. As advanced carbon materials have controllable porous structure, high surface area, high conductivity, high temperature stability, excellent anti-corrosion property and compatibility in composite materials so they can be employed in energy storage as electrocatalysts, electro-conductive additives, intercalation hosts and ideal substrate for active materials. Meanwhile, the chapter sums up the required demands of advanced carbon materials for technological innovation and scientific applied research.

Keywords: Graphene, Drug Delivery, Porous Carbon, Physical Properties, Chemical or Physical Methods, Energy Storage, Catalysts

1. Introduction

Nowadays, Carbon science is immensely popular in several areas of material, nanoscience and, engineering [1] because of its unique and fundamental properties. Basically, the word carbon meaning Charcoaloriginates from Latin *carbo* [2]. It's among the most plentiful component on the earth. Since about 5000 BC, Carbon has been acknowledged and utilized for diverse purposes. From prehistoric times, carbon was primarily obtained from wood that has been used for fuel for millennium years. Graphite is the crystalline form of carbon that occurs naturally. The second allotrope of carbon is diamond and has been adopted as a gemstone. Diamond is extensively used in industry, due to its extraordinary optical properties [3].

In general, the 20th century is identified as plastics while 21st century will be named as 'century of graphene' due to its remarkable physical properties.

Graphite, diamond and amorphous carbon were only carbon allotropes known to exist in the early 1980s [4]. Where amorphous carbon does not have a crystalline structure and is used in various applications like ink, rubber filler, and paint. Carbon has a remarkable capability to bind with numerous other elements to make it essential to nearly all life. The current era is abounding with a variety of novel materials and undeniably the 20th-century capitulates a significantly more materials than previous centuries. Various materials have significant impact on society. Carbon has emerged as the most crucial substance for transforming 21st-century illumination for two reasons, carbon is immensely strong and very lightweight [5].

Discovery of fullerene developed the new aspect to the cognizance of carbon science, and it is the fourth allotrope of carbon at the nano level in which Spherical fullerene are buckyballs (C_{60}) is most common. In 1970, the existence of C_{60} was purposed by E. Osawa. Buckyball was discovered, in 1985 by R.F. Curl, and co-workers. In 1996, R.F. Curl and co-workers win Nobel Prize for this great discovery. Thereafter, in different natural environments, C_{60} was found in rock, on earth, and in space [6, 7]. In buckyballs, atoms are covalently bonded to three nearest atoms in closed-shell [3]. This serendipitous discovery gave rise to a new epoch for synthesized carbon allotropes. The next major breakthrough in this area was the carbon nanotubes synthesis mechanism. Carbon nanotubes were discovered by S. Iijima, in 1996 [8]. By using evaporated graphite, synthesis of semi uni-dimensional carbon tubes was reported forthwith the discovery of fullerenes [9]. Later on, by using the chemical vapor deposition fabrication technique, carbon nanotubes were developed [10]. One of the types of carbon nanotube is single-walled (SWNTs) in which consist of one atom thick layer while multi-walled (MWNTs) many layers of graphitic carbon in the wall [11]. Carbon nanotubes were discovered later but they give new dimensions towards the field of advanced carbon.

In 2004, A. Geim and his colleagues investigated and fabricated graphene, which is the final stage of succeeding progress of carbon-based material. In 2010, Andre Geim and his team won Nobel Prize for their innovative research on graphene. Graphene is considered as a primary constituent of various allotropes of carbon and knowing as a mother of carbon-based materials especially graphite [12]. Graphene has a honeycomb-like structure, that is made up of a single atom thick sp^2 hybridized carbon atom (**Figure 1**).

Diverse allotropes of carbon materials are mostly employed in renewable energy resources for the generation and storage of energy. Carbon nanomaterials

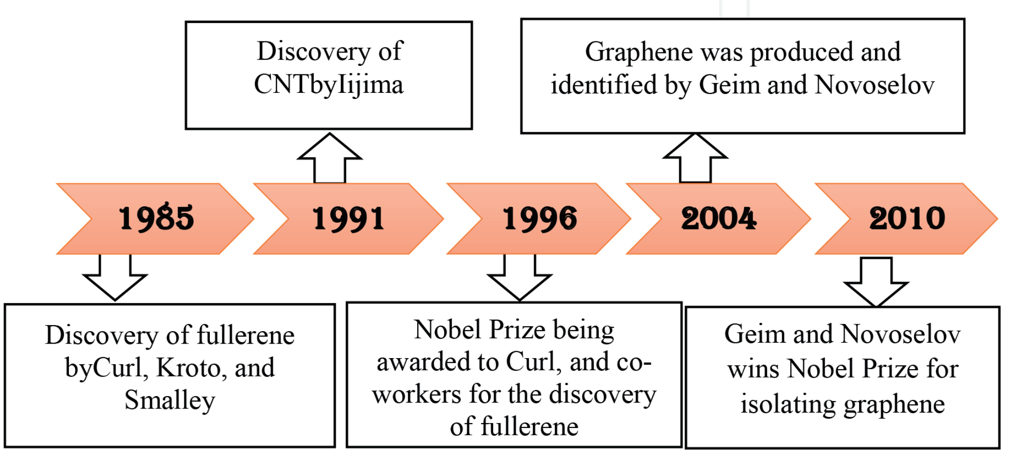

Figure 1.
Time line of advanced carbon materials.

offer tremendous potential for enhancing biology, medicine [13], electronics, energy technologies [14], and drug delivery. Scientists are currently working feverishly to achieve the inimitable electrical, mechanical, and thermal properties of their carbon materials for potential applications. Hence the interest in synthesis and applications of sustainable materials is emerging. Especially, for the sake of applications in future chemical and energy sector are becoming recognized. This chapter will introduce different fabrications methods for sustainable carbon materials as well as highlights their applications in essential energy and environmental-related field.

2. Fabrication of advanced carbon materials

With the innovation of industrial and commercial growth, the globe is confronted with a slew of crisis, including energy shortage and environmental issues, which have hampered the advancement of human civilizations. Researchers have employed a variety of methods to address these issues and have achieved certain results [15]. The synthesis for advanced carbon materials (Carbon nanotubes, Graphene and, fullerenes) has been developed tremendously. So, this material can fabricate by two methods physical methods and chemical methods. During the chemical production of nanoparticles, it is feasible to control particle size at a nanometer scale [16]. While the devoid of solvent and uniform nanoparticle dispersion is a fundamental aspect of this physical method over the chemical method [17].

3. Physical methods

3.1 Fabrication of carbon nanotubes via laser ablation

Smalley and his team established, method of laser vaporization for the preparationof fullerene as well as carbon nanotubes [18]. it was initially used for the synthesis of fullerene and then later it is used in the production of CNTs, particularly single-wall CNT [19]. Laser ablation is a technique that is used for the synthesis of carbon nanotubes. A furnace, graphite target, reactor tube and, laser beam source is used in this process (**Figure 2**).

A small graphite pellet is positioned at the mid of the quartz reactor tube inside the furnace at a specific temperature. Once the air from quartz has been evacuated, temperature of the furnace is raised to 1000°C- 1200°C. The quartz tube is saturated with inert gas. Scanning the surface of the pellet by beam of laser, graphite is vaporized whereas to preserve the smooth and homogenous surface. When gases

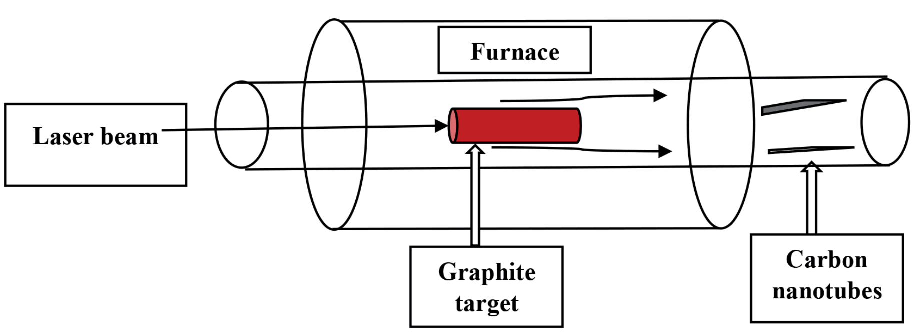

Figure 2.
Pictorial diagram of laser ablation method.

flow through chamber as a result, carbon constituents obtained via sublimation of graphite are displaced. Coalesce phenomena took place in gaseous state. After that, they deposit on the surface of the collector of cooled copper. The fundamental distinction between pulsed and continuous laser vaporization is that pulsed laser produced significantly higher power density. Many parameters influence the properties of CNTs synthesized by the pulsed laser deposition process (PLD), including laser properties, target material compositional and structural properties, chamber pressure, and chemical composition [5].

3.2 Fabrication of carbon nanotubes via electric arc discharge

By using arc discharge method, Zhai etl fabricated amazing form of carbon [11]. The AC/DC arc discharge technique may be used to prepared CNTs. The electric arc discharge synthesis method involves high voltage delivered between two graphene electrodes and high temperature. The synthesis process successfully accomplished by filling a chamber with inert gas, such as He/Ar gas. Potential difference is supplied among two water-cooled electrodes that are made up of graphite. Subsequently, gradually electrodes are brought closer together till the gap among the electrodes narrows reaches the point, where electric arc collapse happening. Afterward, sublimation of anode occurred, yielding the plasma at the region among the two electrodes, wherever temperature approaches 6000°C high enough to cause graphite sublimation (**Figure 3**).

The carbon atoms are evacuated from the solid during sublimation, the pressure is extremely high. Then these atoms migrate to the colder zone of the chamber, allowing a nanotube to deposit to accumulate on carbon. This type of nanotube is produced highly dependent on the composition of the anode. In comparison to other methods, this methodology leads to the growth of CNTs with few structural defects [5].

3.3 Synthesis of graphene via micromechanical exfoliation

Novoselov and Geim developed a very simple efficient method. This method involves, repeat the adhere and peel steps multiple times by using ordinary scotch tape, culminating a few mm -thick flakes of graphite of auni-layer thin specimen.

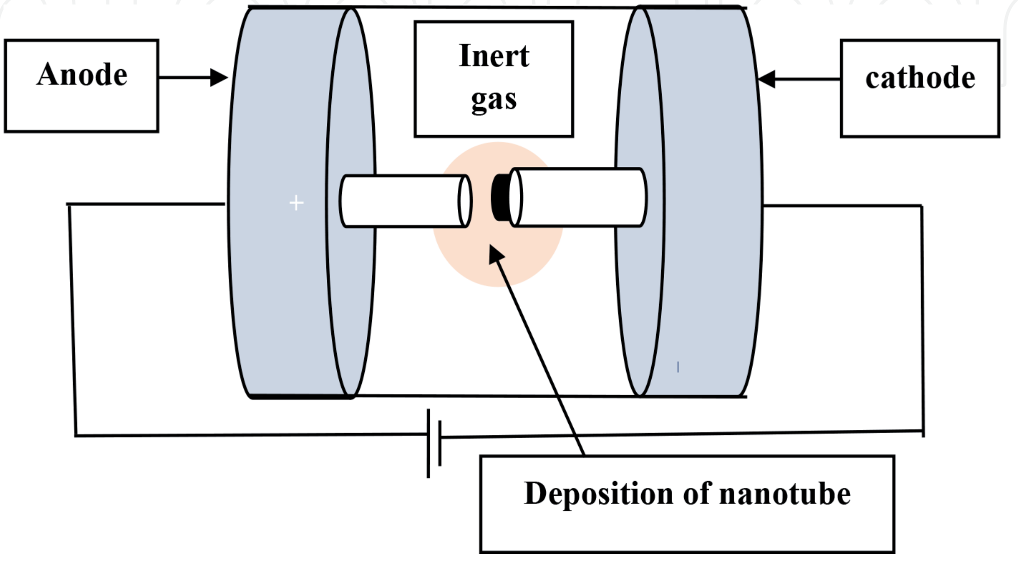

Figure 3.
Schematic diagram of Electric arc discharge.

DOI: http://dx.doi.org/10.5772/intechopen.100213

By using manually mechanically cleavage graphite with scotch tape, the first graphene sheet was produced. Deifying the fact that no two-dimensional crystal can occur underneath the environmental conditions and, also displaying a variety of unique characteristics [20]. Mechanical exfoliation can produce high-quality graphene for characteristics research. But it not appears innovative for the huge areas. Mechanical exfoliation produced particles of graphene, with few microns of sideways dimension [21].

3.4 Synthesis of graphene via arc discharge method

Arc discharge techniquehas beenused to prepared sheets of graphene. For the first time, Rao et al. showed that this method may also be used to fabricate the sheets of graphene [22]. Here graphite is used as an electrode, they used comparatively high hydrogen pressure and produce graphene having 2–4 sheets in the innermost arc area. No catalytic agent has been employed in this process. Furthermore, doping of nitrogen and boron, sheets of graphene, can easily obtained by a nitrogen source (pyridine) and boron source (B_2H_6). Nevertheless, the graphene sheet's dimensions and shape can be optimized [23].

4. Chemical methods

4.1 Fabrication of carbon nanotubes via chemical vapor deposition (CVD)

CVD technique is utmost popular, uncomplicated as well as cost-effective for producing Carbon nanotubes, at relatively low temperature. In this approach, a gaseous carbon source is used. Transmit energy to the gaseous state of carbon molecules by using av ariety of energy sources such like a Heating coil or plasma source. As a source of carbon, CVD employing different hydrocarbons such as, carbon monoxide/methane. During this process, a substrate is coated with a metallic catalyst is heated around 700°C.When two different gases, one is actually carrier gases (Argon /Nitrogen/hydrogen) and, hydrocarbon transported via chamber, growth begins (**Figure 4**) [24].

When chamber is heated up using heating coil, then disintegrated gasses causing a reaction between reactive species from the gas and catalyst resulting in carbon deposition on a substrate. Through an elimination system, hydrogen gas as a residue will eliminate from the chamber [25]. The temperature range for the vapor deposition is 600°C-1200°C. The vapor of hydrocarbon will mix with a metallic catalytical agent till carbon and hydrogen are produced. While carbon will soluble in metallic substrate and evaporation of hydrogen will occur [23].

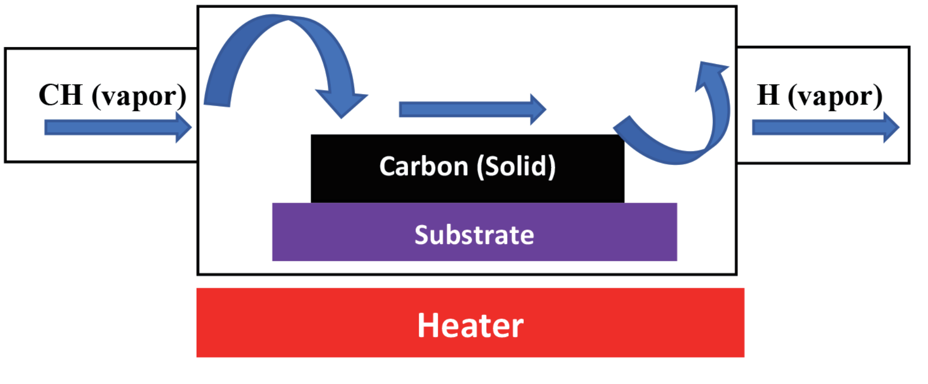

Figure 4.
Schematic diagram of CVD.

4.2 Fabrication of carbon nanotubes via hydrothermal method

The latest approach known as a hydrothermal method, use to synthesize the carbon nanotubes (CNTs) at low temperature, reducing the cost of CNTs production on a wide scale. Furthermore. Hydrothermal synthesis of materials has several advantages, environmentally Benefield, simple and quick. CNTs are made by utilizing the hydrothermal method, which uses ferrocene as carbon percussor and sulfur as a catalyst. Under constant stirring, sulfur and ferrocene have been mixed with NaOH solution containing ethanol and distilled water. Under the ultrasonic bath, the mixture has been sonicated at ambient temperature and constant stirring. The homogeneous solution is transferred to an autoclave reactor for hydrothermal treatment in an electric oven. Once the reaction is completed, the autoclave reactor has been cooled at room temperature. Black participate in the autoclave is filtered, and washed with ethanol, HCl, and then distilled water, until the pH 7 of washing solution is obtained [26].

4.3 Synthesis of graphene oxide (GO) via Hummer method

W.S. Hummers and R.E. Offeman developed this method in 1958 [27]. This method is appropriate for the synthesis of graphene oxide (GO) on wide-ranging. Hummer method emphasized three Phase responses [28]. Intercalation at a lower temperature around 5°C, moderate temperature approximately 35-40°C oxidation of graphite intercalation compounds, and hydrolysis due to higher temperature. For the preparation of GO, untainted graphite, concentrated sulfuric acid and, sodium nitrate is added to the flask. Kept that flask at temperature 5°C in an ice bath, under constant stirred for few minutes. After that, to avoid intense reaction at a certain spot, potassium permanganate has been slowly added to the flask. Next step, to remove the ice bath. Temperature of the reaction is gradually raised to a maximum temperature that is 35-40°C, and maintained for half an hour with continuous stirring. Demineralized water is then added to the mentioned suspension. As a result, hydration of heat, producing a large exotherm of approximately 98°C. After that bath process is maintained at maximum temperature. Later on, deionized water and hydrogen peroxide have

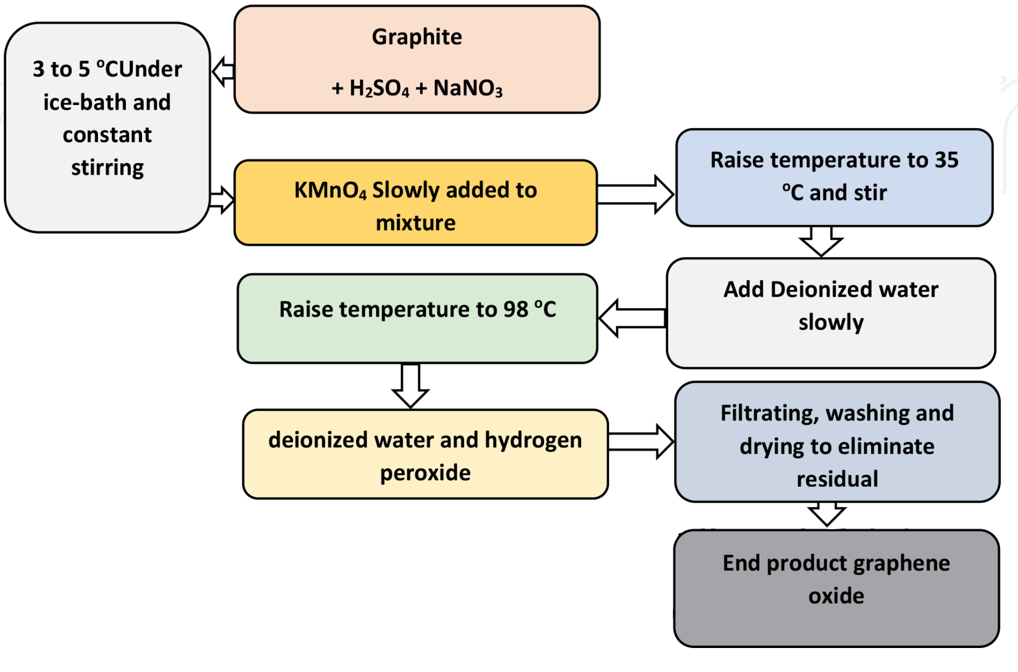

Figure 5.
Schematic flow chart of GO synthesis by Hummer's Method.

been added to finish the reaction. Vacuum filtration extracts the finished product from the solution, which is in yellowish/brown color. The GO granules are then rinsed five times in dilute hydrochloric acid. and warm deionized water to eliminate any residual Mn ions or acid [29]. The graphene oxide (GO) has been synthesized via filtering and drying under the vacuum at room temperature (**Figure 5**).

4.4 Synthesis of graphene oxide (GO) via modified Hummer method

Modified Hummer method is used to synthesized GO. In this procedure, graphite is added to concentrated sulfuric acid and phosphoric acid (relatively 9:1 ratio of volume) [30]. Stirred for 10–20 minutes in bath ice. A double amount of potassium permanganate has been gradually added into the mixture under stirring. Keeping temperature of solution around 3-5°C solution. The mixture has been reacted for 2–4 hours in a cold bath. Once again mixture has been stirred, at a 38–40°C water bath. Consequently, for one hour, the temperature of the mentioned mixture is maintained at 98°C [31]. Deionized water is continually added. Along with hydrogen peroxide also has been added dropwise in the said suspension. After filtration, mixture is washed with deionized water and Hydrochloric acid multiple times. At last, the end product is dried to get final outcome of GO (**Figure 6**).

4.5 Fabrication of reduced graphene oxide (rGO) via Tour method

Tour's group developed an improved version of Hummer's method in 2010 at Rice University. In the mixture of H_2SO_4/ H_3PO_4 (9:1), they replaced the sodium nitrate with orthophosphoric acid and increased the quantity of $KMnO_4$. There is no generation of hazardous gas such as NO_2, N_2O_4, or $ClO_2$are regarded as the benefit of this method, and temperature is easily controllable in Tour's method. According to the author, the existence of orthophosphoric acid leads more intact graphitic basal plane [32]. Tour's method is most efficient for GO as, it is inexpensive, non-toxic and also, environmentally benign [33].

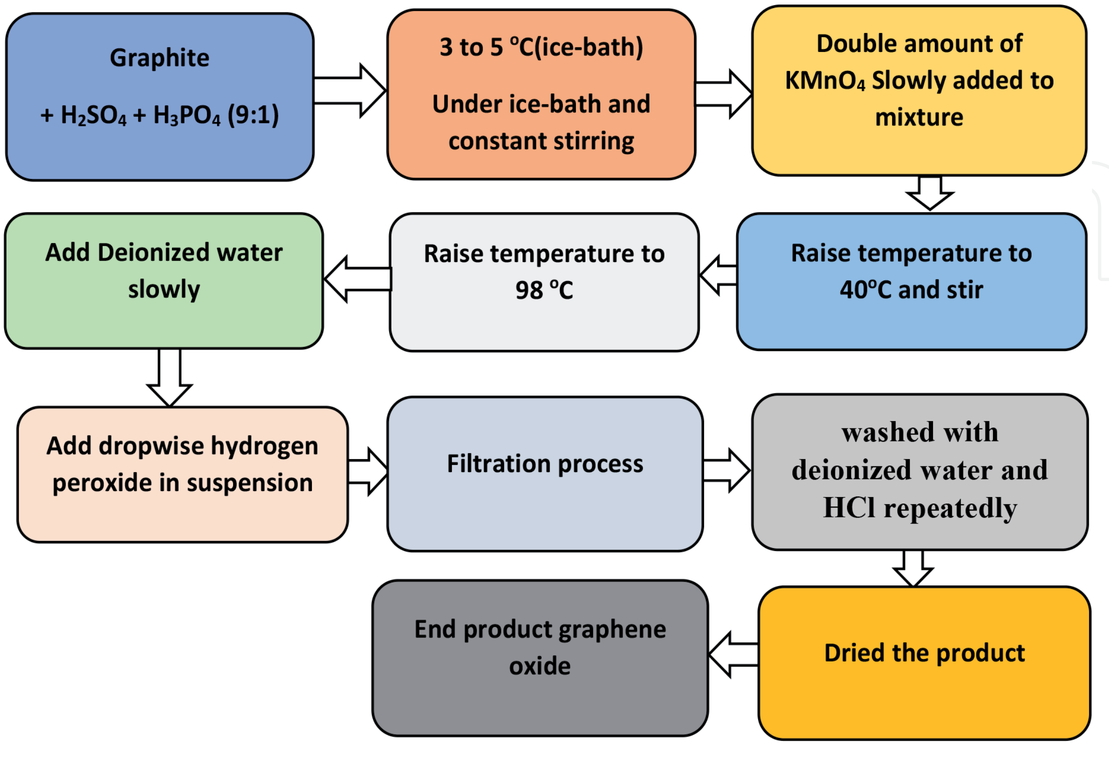

Figure 6.
Schematic flow chart of GO synthesis by Modified Hummer's Method.

5. Applications of advanced carbon materials

Advanced carbon nanomaterials are receiving a lot of attention of scientific research in last few years owing to their unique mechanical, thermal, chemical, optical and electrical properties. Advanced carbon materials, comprising of graphene, fullerene, carbon fibers, activated carbon and carbon nanotubes are considered as backbone of material science and technological innovation [34]. These advanced carbon materials also find applications in electronics, organic photovoltaic, energy conservation technology and drug delivery as illustrated in **Figure** 7 [35].

5.1 Drug delivery

The advancement of drug delivery systems is appealing as it permits to improve the therapeutic properties of already existing drugs. The main purpose of developing an improved drug delivery system (DDS) is to transport therapeutic agents to the diseased area in a controlled way with few side-effects on other healthy tissues [36]. In the last few years, the advancement in nanotechnology has avoided some problems in this area by inserting nanosacled drug carriers with useful applications in drug delivery system (DDS). Among different nano-sized drug carrier, advanced carbon materials have been extensively discussed for delivering therapeutic molecules, owing to their advantageous physical as well as chemical characteristics [37].

Recently, graphene has been explored as novel and inexpensive DDS with the possibility of being employed for systemic, targeting and local DDS [38]. Graphene is considered as one of the best nanocarrier for drug delivery because of its many reasons. Firstly, it can load more drugs than other nanocarriers owing to larger surface provided by arrangement of atoms in two dimensions. Secondly, graphene and GO are suitable for different delivery environments due to their high chemical and mechanical stability. Thirdly, toxicity and side effects of graphene and GO can be reduced by simple functionalization process such as coating with biocompatible material [39]. As graphene has an excellent ability to deliver protein, peptide and nucleic acid into the cell by crossing the cell membrane so it has been explored for delivering various therapeutics drugs, including antibodies, genes, antibiotics, anti

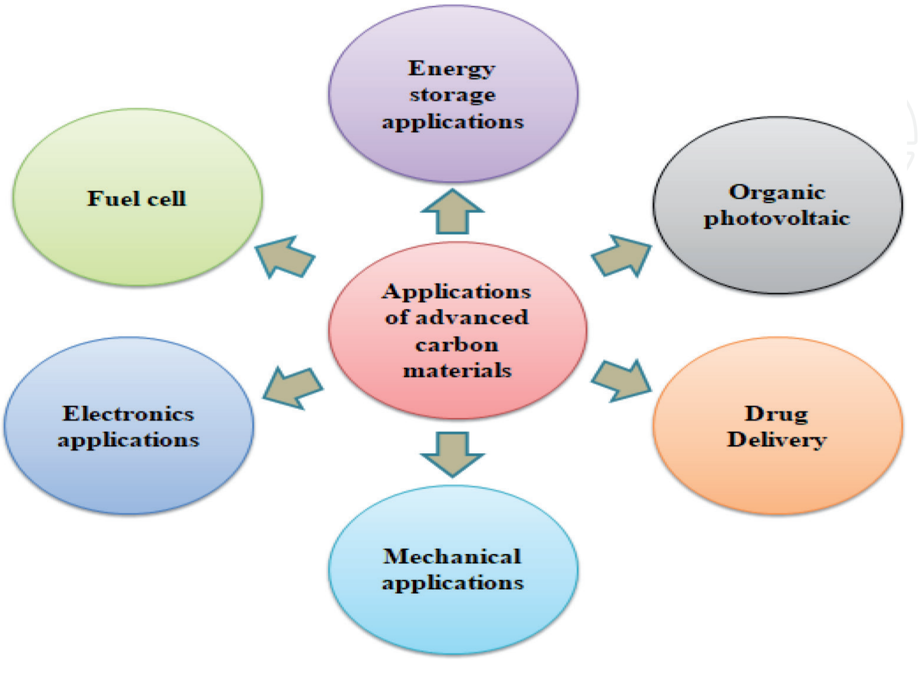

Figure 7.
Advanced carbon material's applications.

cancer medicine, RNA, DNA and insoluble drugs. Delivery of multiple drugs at once by graphene based nanomaterials has also been investigated for chemotherapeutic efficacy [40].

In addition to graphene, carbon nanotube (CNT) has been investigated as fast and effective nanocarrier for delivering therapeutic molecules. It has become an attractive task for many research groups for its excellent drug delivery applications owing to its unique biological, physical as well as chemical properties [41]. CNT also has ability to attach desired functional groups on its outer layer due to its hollow monolithic structure, which makes the CNT a promising nanocarrier for drug delivery. Furthermore, functionalized CNTs can easily penetrate into the cells so they have potential to work as vehicles for drug delivery of small therapeutic molecules [42].

In addition, fullerene is also considered a promising material for drug delivery in the body as catalyst and as a lubricant. It is mostly used to deliver the drugs for cancer therapy, drugs needed to enter the brain and -tumor drugs. It acts as hollow cages to capture other molecules. That is how it delivers drug molecules to the site of action inside the body [43]. It can also transport multiple drugs to different tumors by combining monoclonal antibody. Fullerene is efficient for delivering the drugs owing to its capability to pass blood through brain barrier, deliver directly to the targeted cells, not dissolve before reaching the targeted region and carry the load of multiple drugs [44].

5.2 Energy storage applications

In recent years the demand for highly efficient energy storage devices has increased significantly and a lot of work has been done to develop advanced electrode materials. In this respect, advanced carbon materials have been widely investigated for sustainable clean-energy storage systems owing to their excellent physicochemical and thermo-mechanical characteristics [45]. As advanced carbon materials have controllable porous structure, high surface area, high conductivity, high temperature stability, excellent anti-corrosion property and compatibility in composite materials so they can be used in energy storage devices as electrocatalysts, electro-conductive additives, intercalation hosts and ideal substrate for active materials [46].

Within family of advanced carbon materials, graphene is attracting a lot of scientific attention for its remarkable characteristics including significant surface area, mechanical stability and excellent electrical conductivity, making it suitable to use as electrodes in energy storage systems [47]. They can used to increase the efficiency of currently used energy storing devices for instance super-capacitor and Lithium ion batteries as well as make next generation devices such as Sodium ion batteries, Lithium sulfur batteries and Lithium O_2 batteries, more practical. In supercapacitor, in order to form an effective electric double layer coating, graphene is used in the carbon coatings. These supercapacitors are then utilized to store large amount of energy. Graphene is also used as electrode material in supercapacitor and pseudocapacitors [48].

Carbon nanoube is also another promising material to be used in different energy storage applications. It is used as electrodes in supercapacitor and lithium ion batteries owing to its extraordinary tensile strength, electrical conductivity as well as ultrahigh surface region. Energy storage devices employ CNTs as additives in order to increase electrical conductivity of cathode and also as anode components [49, 50].

Apart from graphene and CNTs, activated carbon also finds its potential as electrode material in energy storage applications due to its wide surface region and excellent electronic conductivity. These properties can be increased by adding other materials such as polymer and other carbon based materials [47].

Fullerene is also used in advanced energy storing devices as electrodes because of their being lightweight, controllable electrochemical performance, flexibility and excellent electrical conductivity [51].

5.3 Fuel cell applications

Electrochemical fuel cell technology is a source of continuous supply of energy and is important for providing sustainable energy conversion system. Fuel cell has become a unique device for energy storage applications varying from mobile phones to power plants because of their excellent efficiency, high performance and less pollutant's emission [52]. For development of fuel cells, one of the crucial components of fuel cell is catalyst support. Catalyst support determines the level of catalyst dissemination and increases the catalyst reactivity. The main characteristics of catalyst support include large surface area, excellent thermal and electrical conductor, stable in different types of working media and good absorbent to allow reactant movement. Catalyst support is necessary to improve fuel cell's efficiency [53]. All these properties are possessed by advanced carbon materials. In fuel cells, advanced carbon materials are used as catalyst as well as catalyst support in order to enhance cell performance. As compare to other materials, advanced carbon materials have several advantages, such as good stability in alkaline and acidic media, electric conductivity and wide surface region. Moreover, these advanced nanomaterials are also used in membranes electrode assemblies (MEA) in fuel cell applications [52, 54].

Among these advanced carbon materials, graphene is favorable for energy conversion systems owing to its certain characteristics including high tensile strength, ultrahigh surface area, chemically stable as well as electronic conductivity, making it a potential candidate for fuel cell applications [55]. Due to all these extraordinary properties, graphene is mostly employed as electro-conductive electrode, catalyst support, bipolar plates and additives in fuel cell technology as shown in **Figure 8**.

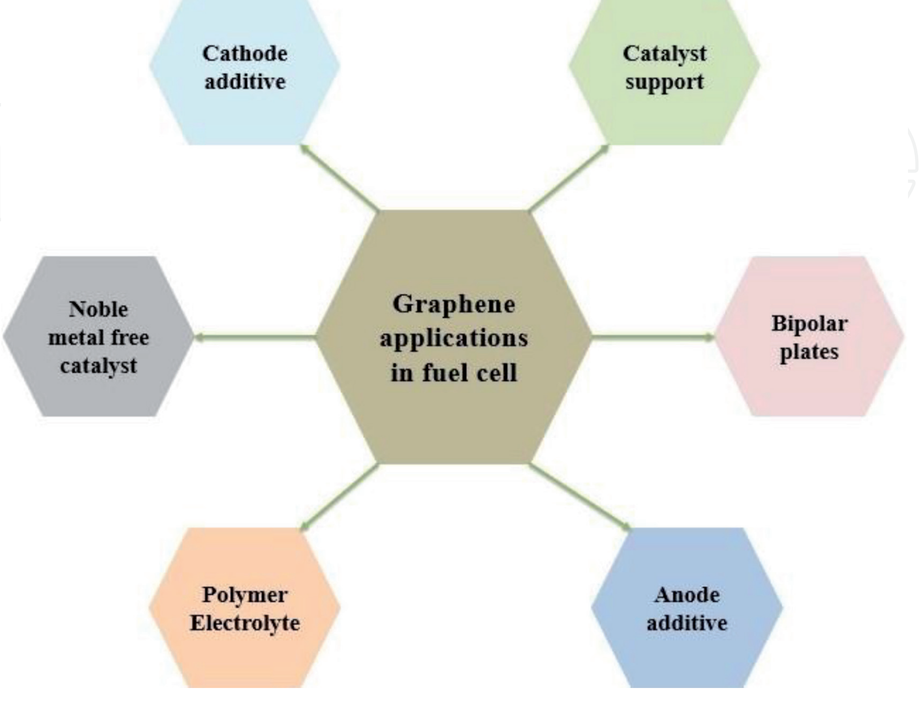

Figure 8.
Graphene's applications in fuel cell technology.

As an additive, graphene is used in electrodes either individually or mix with other carbon based materials [56]. They are incorporated in electrodes (anode and cathode) in order to enhance reactions in fuel cell. So in this way graphene offers its potential as catalyst to enhance fuel cell performance [57].

Besides graphene, carbon nanotubes are also favorable material for fuel cell applications. Properties of multi walled carbon nanotubes (MWCNTs) can be modified via functionalization process in order to produce good combination and improve performance to be used as catalyst support. Furthermore, they can be incorporated in the mixture of platinum/carbon catalyst at the anode to increase the efficiency of the catalytic reactions in the fuel cell [54]. Nitrogen-doped carbon nanotubes have been employed in fuel cells in order to decrease the oxygen level at the cathode. Carbon nanotubes in fuel cells are also used to reduce the demand of metals that are utilized as catalyst as well as enhance the fuel cell's efficiency.

As a catalyst support, carbon nanotubes have efficiently improved the catalyst performance and usage. The fuel cell employing carbon nanotubes as a catalyst support possess larger current density and high performance as well as catalytic activity [58].

In fuel cell technology, fullerene also finds its potential applications as electrocatalyst support at the anode for fuel oxidation reaction, for oxygen reduction reactions occurring at cathode and as proton conducting membrane [59].

5.4 Organic photovoltaic applications

Recently, organic photovoltaic (OPVs) have gain the interest of many research groups because of their usage as conformal, flexible, lightweight and inexpensive power supplies for different commercial applications. OPVs are most effective transformative solar technology made of earth abundant and nontoxic materials on larger scale. Their performance for commercial applications can be improved despite their high capability in large scale development [60]. In order to meet these performance goals, advanced carbon based materials are extensively used as transparent flexible electrodes, hole transporters and electron acceptor in OPV devices. Advanced carbon-based photovoltaic devices have attracted much attention for both scientific research and commercial applications. Advanced carbon nanomaterials namely fullerenes, graphene, activated carbon and carbon nanotubes possess attractive properties to be employed as active materials for the development of OPV devices [61].

In OPV devices, organic solar cell is most extensively used device for potential applications. The aim of organic solar cell is to provide effective and low cost energy production photovoltaic device as compared to already present solar technologies. Generally, organic solar cell is a very simple device made up of small organic molecules, polymers, or mixture of both materials with or without other nanomaterials added into whole device [62]. These cells are not only flexible but also their fabrication cost is just one third of the price of silicon cell. They can be inserted in infrastructures including walls, windows, car windshields and many others [60].

Although graphene has single atom thick sheet structure but due to high hole transport movement and larger surface region, graphene finds its applications in organic solar cells [30]. In organic solar cells, graphene thin films are extensively utilized as window electrodes. There are many advantages of using graphene in these cells. Firstly, it generates a window for inducing photon energy in a wide range of wavelengths (from UV to far infrared) inside solar cells. Secondly, it builds a flexible transparent device with robust architecture. Thirdly, it possesses high charge transfer mobility at the interface of electrochemical cells and allows for more heat dissipation [63].

In addition to graphene, Carbon nanotubes (CNTs) have unique characteristics, such as excellent electrical conductivity, that make them ideal for combining with conducting polymers to create composites being used in organic solar cell. These cells have been made by incorporating carbon nanotubes into conjugated polymers. In principle, carbon nanotubes and their composites can replace all parts of a solar cell, including the light sensitive component, carrier selective contacts, passivation layers, and transparent conducting films [64]. Over the last decade, carbon nanotube has been employed in organic solar cell as additives, carrier transporters, transparent electrodes and light absorbers. Single walled carbon nanotube has been widely utilized as an electron donor with fullerene-derivates as an acceptor in organic solar cell using carbon nanotubes in photoactive layer to produce a type II heterojunction [65].

With the discovery of photo-induced electrons transfer from conducting polymers to fullerene, fullerene has been the most favored electron accepting and transferring material for organic solar cell. Importantly, to improve the organic solar cell's efficiency, the thickness of photoactive layer can be decreased by utilizing single-crystal fullerene [66].

5.5 Electronics applications

Advanced carbon materials are well recognized for their usage in electronics because of their distinctive properties. Among advanced carbon materials, graphene is the outstanding material with its attractive characteristics which make it preferable choice for advanced electronics applications. Graphene finds its potential to bring revolution in electronics due to its remarkable strength, thermal and electrical conductivity and electron mobility [67]. In electronics graphene is mostly used as transistor, interconnect, sensor and thermal management. It's one of the most efficient electrical conductors on the Earth.

In electronics and integrated circuits, the characteristics of graphene have made it a viable alternative to silicon and the basis for developing superconductors which permit to generate higher voltage lines that will effectively transfer energy to our houses [68]. Microchips and transistors, both fundamental components in almost all electrical devices, can be made from graphene. Graphene is used to build circuitry of computer resulting in the development of significantly faster computers with low power consumption than existing silicon. It is used to build circuitry Touch screens for cell phones and tablets can be improved by using graphene as a coating [69].

Besides graphene, carbon nanotubes for electronic applications are also interesting topic for research and printable carbon nanotube inks are making their way to the market. Carbon nanotubes are utilized in the manufacture of transistors and are used as conductive layers in the rapidly expanding touch screen sector. In some applications, carbon nanotubes are thought to be a good substitute for Indium tin oxide (ITO) transparent conductors [70]. For instance, carbon nanotubes, when fabricated as transparent conductive films (TCF), might be utilized as transparent, highly conductive and inexpensive alternative in flexible displays and touch panels. Significant development has been achieved on carbon nanotubes field effect transistor (FET). Carbon nanotube-based field effect transistors (FETs) exhibit operating characteristics that are almost comparable to those of silicon-based components [71].

Single-wall carbon nanotube (SWCNTs) is promising candidate for the channel material of flexible thin film transistor (TFT). Thermal management of electrical circuits is achieved using large structure of carbon nanotubes. Random networks of SWCNTs have also been used to fabricate integrated logical circuits. Carbon nanotubes also act as a rectifying diode [72]. In molecular electronics carbon nanotube is good candidate for connection because of their structure, electronic conductivity as well as capability to be precisely generated. It is also recently revealed that SWNTs, when employed as interconnects on semiconductor devices, they can transmit electrical signals at high speed [73]. Fullerene is also used in electronics in a variety of ways, including as a diode, transistor, and photocell. Moreover, fullerene also behaves as device interconnects [74].

5.6 Lightweight mechanical applications

One of the most intriguing properties of graphene is that it is the lightest and strongest substance known. It is lighter than aluminum and more elastic than rubber. The reason that graphene stands out as a reinforce ingredient in composite material is its outstanding intrinsic mechanical characteristics, such as stiffness, strength, and toughness [75]. Currently, graphene is expected to be used (possibly incorporated with plastic) to make a material that would substitute steel in airplane structures, improving its performance, range, and weight. Because of its electric conductivity, it is utilized to cover airplane outer surface to protect it from electrical damage. This covering is also utilized to determine strain rate, alerting the pilots to any variations in the stress levels on the airplane's wings. The advancement in high strength demanding potential applications just like body armor for armed persons is possible with the help of useful properties of graphene [76]. Graphene is a promising material for the development of speakers as well as electrostatic audio microphones because of its lightweight property, which in turns show fairly good frequency response. For applications considering strength and weight as limiting factors such as in aerospace industry, graphene can be added into a variety of composites. It is incorporated in different materials in order to make existing materials more stronger and lightweight. So a composite material that is more lighter and stronger than steel, gives the necessary strength required for the aviation industry and save more money on fuel consumption. This is the main reason of incorporating graphene into these materials [77, 78].

Carbon nanotubes also possess extraordinary mechanical properties. The Young's modulus of carbon nanotubes is about 1TPa and their tensile strength is about 11–63 GPa. Due to these unique properties, carbon nanotubes have gained much attention for many mechanical applications such as rotational actuators, nanometer cargoes, high frequency oscillators and nanometer tweezers. Extraordinary mechanical properties of carbon nanotubes make it preferable material for load-bearing reinforcement in composite materials as well as also for structural applications [79]. Moreover, low specific weight and high young modulus of SWCNT enable them to employ as ultimate mechanical resonators for analyzing mechanical motion in quantum field. Tip used in scanning probe microscopy can be made of carbon nanotubes due to its high elasticity property that avoids the mechanical destruction of tip when in contact with the substrate. Carbon nanotubes are also widely used in various sensor applications such as in mechanical sensors [80].

6. Conclusions and future directions

Advanced carbon nanomaterials are receiving a lot of attention of scientific research in last few years owing to their unique mechanical, thermal, chemical, optical and electrical properties. Advanced carbon nanomaterials, comprising of graphene, fullerene, carbon fibers, activated carbon and carbon nanotubes are considered as backbone of material science and technological innovation. These nanomaterials are fabricated by using different physical and chemical methods to get high materials with excellent characteristics. Advanced carbon materials also find applications in electronics, organic photovoltaic, energy conservation technology and drug delivery etc. In future these advanced materials can be used to develop several materials with different applications. A lot of research is taking place for producing these materials on industrial level. These advanced materials are the future of sustainable energy production and storage devices owing to its capability to store energy on large scale. Fuel cells also in the near future are thought to replace battery based energy systems. Graphene sheets may have the potential to be a game-changing use in microelectronics. The demand for advanced carbon materials will be further growing for technological innovation.

Author details

Aneeqa Bashir*, Azka Mehvish and Maria Khalil
Department of Physics, University of the Punjab, Lahore, Pakistan

*Address all correspondence to: aneeqa.physics@pu.edu.pk

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