



FULLERENES: SYNTHESIS AND APPLICATION

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Abstract

Fullerene molecules are composed entirely of carbon and can take the form of a hollow sphere, an ellipsoid, a tube, or many other shapes and sizes. The paper reports the synthesis and application of fullerenes. In the study, different types of fullerenes, synthetic methods, and applications were considered. Out of the two synthetic approaches, the laser irradiation of PAHs was mostly preferred to the electric arc heating of graphite, though it involves purification with chromatography. The findings reveal that the functionalization of fullerenes increases its application in medicine, photovoltaics, polymeric materials, water purification/environment, hydrogen storage, energy storage, and reinforcement composites. Greater study of fullerene molecules is needed, especially their incorporation into supramolecular assemblages and nanostructures to attain excellent performance in their respective tasks.

Keywords: Applications, Fullerenes, Synthesis, Polymers, Fullerene

Introduction

Fullerene carbon clusters have attracted a lot of attention in a variety of scientific disciplines in recent years. This is based on the idea that they have a large range of isomers and homologous series, with similar sizes and forms. A fullerene is an allotrope of carbon that has fused rings of five to seven carbon atoms that are joined by single and double bonds to form a closed or partially closed mesh. The molecule can take on a variety of forms, including a hollow sphere, an ellipsoid, a tube, and many others. Carbon nanotubes are often formed when the carbon molecules are organized in a cylinder-like shape (Jinno et al., 1997; Beg et al., 2011). Each carbon atom in a fullerene molecule is connected to three other carbon atoms, and the molecules are made of carbon. They have a closed cage-like icosahedral symmetry and are composed of 20 hexagonal and 12 pentagonal rings (Ali et al., 2004; Siber, 2020). Diamond and Graphite are a couple of additional carbon allotropes. Graphite and fullerenes share a similar structure with interconnected carbon atoms arranged in hexagonal and pentagonal rings. However, fullerenes may also feature pentagonal rings (Ali et al. 2004). Three different carbon allotropes' structural makeup and atom arrangement are shown in Figure 1.

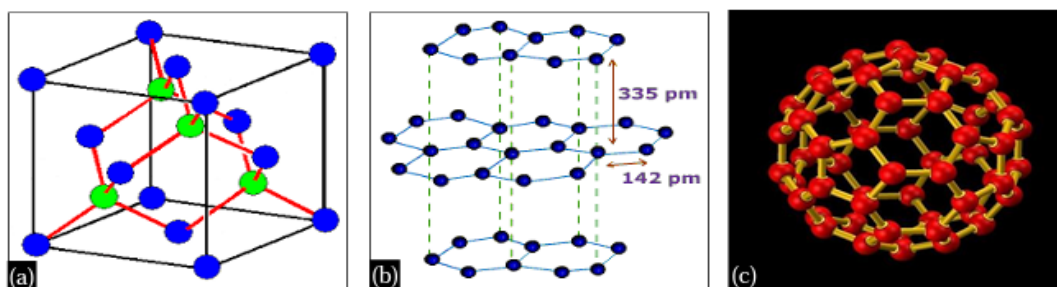


Figure 1: Allotropes of carbon (a) Diamond (b) Graphite (c) Fullerene (Yadav, 2017).

Fullerenes and its derivatives have recently been incorporated into commercial products, moving from basic research on cluster carbon structures to industrial production. In contrast to graphite and diamond, fullerene has a high chemical reactivity. There have been numerous distinct chemical processes and fullerene derivatives described thus far in the scientific literature (Lopez et al., 2011). As an electron-deficient alkene, spherical fullerene reacts with electron-rich species with ease. While keeping the distinctive intrinsic characteristics of fullerenes, attachment of various polar functional groups or molecules on the fullerene core overcomes nearly complete insolubility and achieves adequate biological availability (Lopez et al., 2011)

Fullerenes are chemically stable but not completely inert. Fullerenes can function as an electrophile in chemical processes. It is described as an oxidizing agent and functions as an electron-accepting group. Alkali or alkaline earth metal-doped or crystalline fullerenes exhibit superconductivity and ferromagnetism. Fullerene is completely insoluble in water and other polar solvents but is soluble in 1,2-dichlorobenzene, dimethylnaphthalenes, and 1-chloronaphthalene. It is only mildly soluble in toluene and benzene because the carbon atoms are a mixture of sp^2 and sp^3 hybridized systems and the bonding has delocalized molecular orbitals extending throughout the structure, fullerene C_{60} has unique chemical characteristics (Lin et al., 2018). Due to its propensity to avoid double bonds in pentagonal rings and poor electron delocalization link, fullerene is not "superaromatic." It, therefore, behaves as an electron-deficient alkene and rapidly reacts with electron-rich species.

Fullerene undergoes a variety of chemical reactions, the most common of which include nucleophilic addition, pericyclic reactions, radical additions, oxidation, electrophilic addition, halogenations, and the creation of endohedral complexes $M=C_{60}$, where M typically refers to a metal atom (Djordjevic et al., 2015). The main processes are electrophilic addition reactions, which are often exothermic (these reactions are accompanied by a change of hybridization of the carbon atoms from sp^2 to sp^3 , which reduces angular strain in the cage). The exothermic heat of the reaction decreases with the number of added ends. Adducts with a high level of addition consequently become unstable. The formation of a large number of isomers, as a result, is one of the main issues with the synthesis of a single derivative (Mohan et al., 2019). For instance, $C_{60}X_2$ with two add ends can have eight regioisomers (23 stereoisomers). Numerous organic compounds and functional groups can form covalent bonds with C_{60} 's cage according to its chemical characteristics (nucleophilic and electrophilic additions,

pericyclic reactions, and radical additions) (Lopez et al., 2011). The most crucial fullerene derivatives for biological applications are those that are water-soluble.

Fullerene is a chemical that only has an even number of carbon atoms. It has 12 five-membered rings and the rest are six-membered rings, forming a three-dimensional cage-like fused-ring polycyclic structure. There is always an even number of carbons in fullerenes. The isomers of fullerenes include homologues ranging from the lowest, most well-studied fullerenes, C_{60} and C_{70} , to the highest fullerenes, C_{240} , C_{540} , and C_{720} . As a result, they are valuable in many scientific domains, such as the separation and identification of chemical species (Jinno et al., 1997; Withers et al., 1997; Baena et al., 2002). A straightforward nucleation pathway results in the spontaneous creation of fullerene molecules in chaotic carbon plasma, which shows that when carbon nucleates, curved, closed graphitic shells wrapped in epitaxial conditions are created (Guillaume et al., 2000). The fullerene structure differs from other crystal structures in that it lacks borders, charges, dangling bonds, and unpaired electrons. These features set fullerene apart from other crystal forms like graphite or diamond, which have edges with electrical charges and dangling bonds. Natural fullerenes typically have a high degree of symmetry. Their structure, which is made up of a sheet of connected hexagonal rings (cage structure), is quite similar to that of graphite (Jinno et al., 1997).

Additionally, each of the twenty prior triangular faces of fullerene is changed into a hexagon, a six-member ring with a carbon atom at each corner and a bond along each edge. Structures that avoid contiguous (edge-sharing) pentagons are especially stable because the molecular strain tends to be concentrated in the five-member rings that are responsible for the closure. It turns out that the smallest carbon clusters for which this is possible are C_{60} and C_{70} (Baena et al., 2002). A fullerene's solubility in water can be increased by adding hydroxyl groups (fullerenols), and it has a variety of applications. Additionally, the availability of fullerenes in macroscopic amounts has stimulated many chemical changes, resulting in the creation of a wide variety of fullerene derivatives (Aleksandar et al., 2013). Fullerenes have been functionalized, making them a useful building block for organic chemistry. This has led to variations in their chemical, geometrical, electrical, and photophysical properties.

This study explored the various forms of fullerenes, their synthesis, and their uses in the chemical and pharmaceutical industries based on the special physical and chemical features of fullerenes.

Types of Fullerene

Fullerenes were found in 1985. Subsequently, numerous forms of fullerenes were identified based on structural differences. They are as follows:

i. Nanotubes

Nanotubes have very small dimensions. These are hollow from the inside like a tube with single or multiple boundaries. Nanotubes are mostly used in electronic industries. Figure 2 shows the structure of the nanotube (Collins & Avouris, 2000).

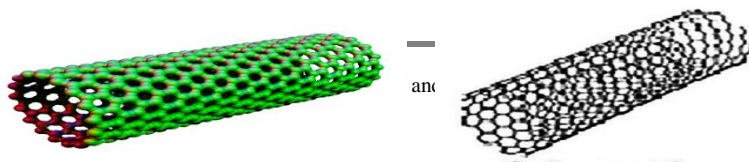


Figure 2: Nano tube (Source: Nasrollahzadeh et al., 2019)

ii. **Megatubes**

Megatubes are bigger in diameter than nanotubes. They have variously sized walls. The primary function of megatubes is to transport molecules of various sizes (Yadav, 2017). The mega-structure tube's is shown in Figure 3.

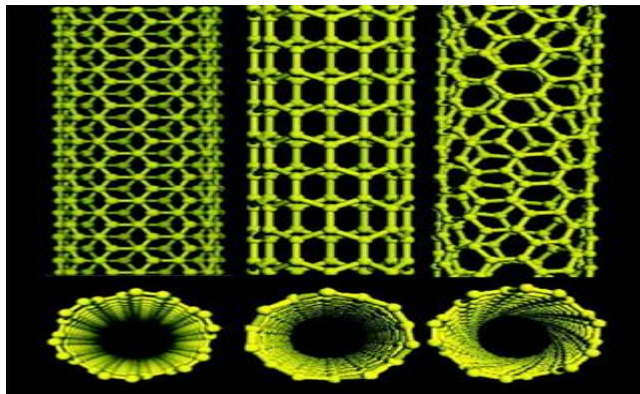


Figure 3: Megatube (source: Yadav, 2017).

iii. **Polymers**

Polymers are formed under extreme conditions of temperature and pressure. These may have various structures, including one-dimensional chains, two-dimensional, and three-dimensional forms (Yadav, 2017). Figure 4 illustrates the polymer structure.

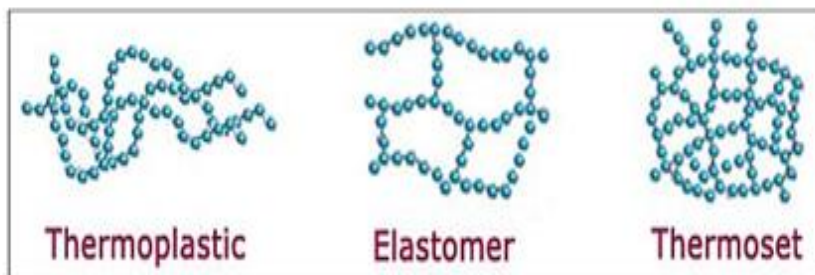


Figure 4: Structure of Polymers (source: Yadav, 2017).

iv. Nano-onions

The form of a nano-onion is that of a sphere. They feature a structure composed of numerous carbon layers with a buckyball core positioned in the middle of each layer. Effective lubricants can be made using nano-onions (Camisasca & Giordani, 2017). The construction of nano-onions is illustrated in Figure 5.



Figure 5: Structure of nano-onions; (Camisasca & Giordani, 2017)

v. Buckminsterfullerene (C_{60})

Buckminsterfullerene is a carbon-based compound with 60 atoms. Twelve pentagons and twenty hexagons make up the cage-like arrangement of these atoms. C_{60} has a soccer ball-like form. The soccer ball's black and white sections are pentagons and hexagons, respectively. All C_{60} of these spots can be filled with carbon atoms to construct the buckminsterfullerene structure. The size of a soccer ball would be equal to the size of the earth if the C_{60} molecule were the size of a soccer ball. The most symmetrical molecule is C_{60} , which has symmetries such as rotational symmetry and reflection symmetry (Bhakta & Barthunia, 2020). A geodesic dome and a buckminsterfullerene have comparable structural views.

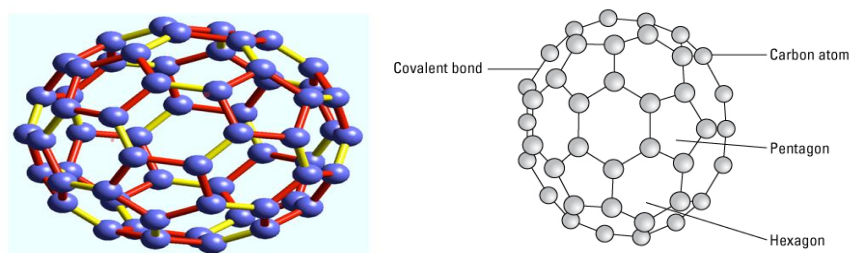


Figure 6: Buckminsterfullerene (Source: Bhakta & Barthunia, 2020).

Synthesis of Fullerenes

In organic chemistry, the fullerenes have proven to be innovative and adaptable building blocks. Initially, fullerenes were synthesized by laser vaporising carbon in an inert atmosphere, but this process only created very small amounts of fullerenes (Nimibofa et al., 2018). But later, by the arc heating of graphite and the laser irradiation of polyaromatic hydrocarbon (PAHs), substantial amounts of fullerene C₆₀ were produced. This paper took into account these two techniques.

Synthesis of fullerenes by Electric arc Heating of Graphite

Geckeler and Samal developed this approach in 1999. A fluffy condensate (Soot) was formed by creating an electric arc between graphite rods in an inert atmosphere. The extractible fullerenes from toluene were present in a small portion of this fluffy condensate. To obtain pure C₆₀, the fullerenes in the soot were then extracted by solvation in a small amount of toluene (Geckeler & Samal, 1999; Lopez et al., 2011). After extraction, the toluene (solvent) was removed using a rotary evaporator from the solid mixture, which was primarily composed of C₆₀ with a small amount of higher fullerenes (Yang & Yan, 2012).

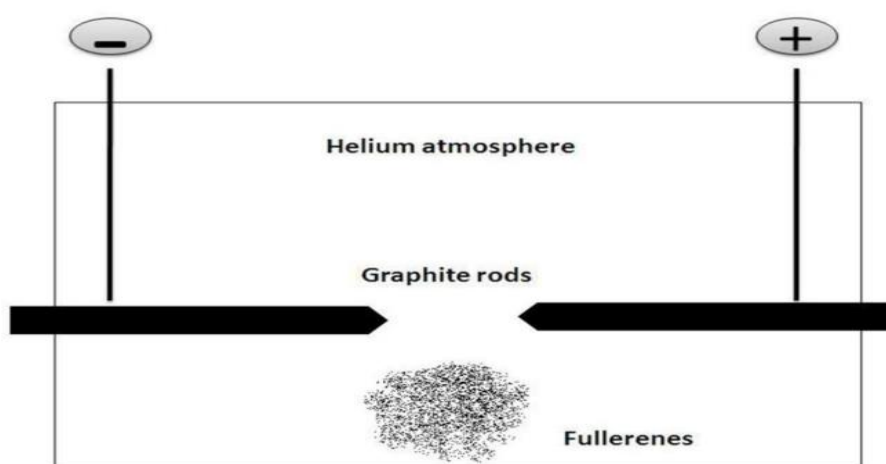


Figure 7: Schematic diagram of the synthesis of fullerene by arc heating (Lopez et al., 2011)

Synthesis by Laser Irradiation of Polycyclic Hydrocarbons (PAHs)

To produce new fullerene homologues that would not be produced in sufficient quantities by the uncontrolled process of graphite evaporation, direct synthesis of fullerenes has been devised. The polycyclic aromatic hydrocarbons (PAHs) that already have the necessary carbon frameworks serve as the foundation for this method of fullerene production. Under the conditions of Flash Vacuum Pyrolysis (FVP), such PAH molecules are "rolled up" to generate fullerenes (Amsharov & Merz, 2012). It has also been reported that a polycyclic aromatic hydrocarbon with 60 carbon atoms produces fullerene C₆₀ when it is laser irradiated at a wavelength of 337 nm (Boorum et al., 2001). The direct production of fullerenes using laser irradiation of polyaromatic hydrocarbon is depicted in Figure 8.

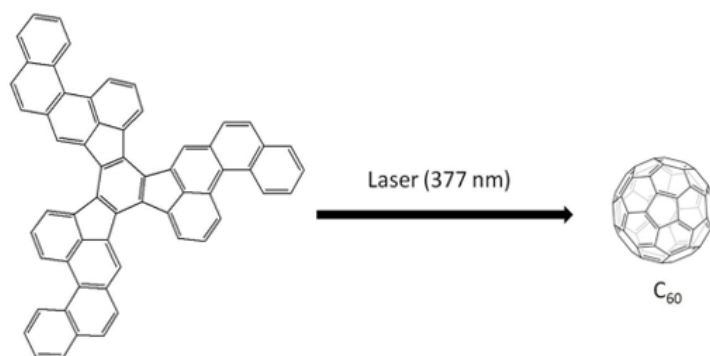


Figure 8: Synthesis of fullerene by laser irradiation of PAHs

Applications Fullerenes

Due to their outstanding physical and chemical properties, many researchers are investigating the use of fullerenes and their derivatives in a variety of sectors, including medicine, photovoltaics, gas adsorption and storage, medicines, and so on.

Medical Application

Fullerene's most desirable characteristics, which have brought them to the forefront of medicinal chemistry, include its size, hydrophobicity, electrical configuration, and three-dimensional capacity. Fullerenes are difficult to dissolve, yet they stand out as potential therapeutic agents due to their carbon cage structure and variety of functionalization choices (Iwamoto & Yamakoshi, 2006).

i. Antiviral and Antibacterial/Antimicrobial Activity

Fullerene and its derivatives have shown antiviral potential, and these properties have been linked to their distinctive molecular cage structure and antioxidant properties (Sybesma et al., 2016). According to studies, HIV protease can be inhibited and complexed with fullerene derivatives (Barras et al., 2015). Additionally, it has been demonstrated that fulleropyrrolidines with two amino groups are efficient against HIV-1 and HIV-2 (Moussa et al., 1997). According to Thakral and Mehta (2006), there is significant hydrophobic contact between the C₆₀ derivative and the surface of the HIV-P active site due to the C₆₀ molecule's similar radius to the cylinder characterising the active site. In molecular simulation studies and tests, fullerene has been demonstrated to stop the spread of HIV-P.

Due to their insolubility in both water and polar media, fullerenes provide significant challenges for biomedical applications (Nakamura & Isobe, 2003). Fullerene cage structures should be changed with appropriate hydrophilic functional groups to enhance biocompatibility. Because of its modified structure and capabilities, the carbon cage may find novel uses in a wide range of biological contexts. Many fullerene derivatives with well-defined structures have been synthesized using regioselective functional group derivatization procedures due to the fullerene carbon cage's many modifiable reaction sites. Because of this, fullerenes can serve as excellent scaffolding for a wide range of bioactive pharmaceuticals. Fullerols and amino fullerene, two hydrophilic derivatives of fullerene, have attracted attention as possible components of water treatment systems due to their antibacterial effects (Fortner et al., 2005; Kang et al., 2009). Photodynamic cytotoxicity against pathogenic germs, including multi-antibiotic-resistant bacteria, has also been proven by attaching several hydroxyl, carboxylic, and glycolic acids to C₆₀ (Yamakoshi et al., 2003; Thota et al., 2012). The biocidal impact of fullerenes is mostly attributed to their photosensitization of organic solvents, which results in the production of reactive oxygen species (ROS) like singlet oxygen and superoxide (Arbogast et al., 1992).

ii. Antioxidant activity

Research indicates that fullerenes have the potential to serve as biological antioxidants. Because of their high number of conjugated double bonds and their low-lying, lowest unoccupied molecular orbital (LUMO), fullerenes can fend off free radical attacks. Fullerene (C₆₀) aqueous solutions made without the use of polar organic solvents not only protect mouse livers from free radical damage but also show no acute or subacute toxicity in rodents (Thota et al., 2012).

Fullerenes have enormous promise in the pharmaceutical and cosmetics industries. Fullerenes are the subject of intensive study to see whether or not they can be used to mitigate the neurodegenerative effects of conditions like Alzheimer's (ALS). Twenty free radicals are neutralized for every C₆₀ radical destroyed due to the sponge-like action of fullerenes. Fullerene-based antioxidants have bioactivities 100 times higher than the best medications on the market at the moment (Fortner et al., 2005)

iii. Drug and gene delivery

Fullerenes have the potential to be used as drug carriers for intracellular delivery because they are biocompatible, selective, and can be engineered to release their contents gradually. They can be made water soluble by coupling hydrophilic species to fullerenes, which makes them perfect for delivering drugs and genes to cells (Isobe et al., 2006). Functionalized fullerenes can be programmed to deliver drugs slowly for maximum therapeutic effect because they can cross cell membranes and bind to mitochondria. Studies have shown that the effectiveness of DNA-functionalized fullerenes is superior to that of commercially available lipid-based vectors (Sybesma et al., 2016). There is growing interest in using cell membranes to deliver medications and biomolecules directly into cells. The development of effective and secure gene or medication carriers is now the main area of interest. Any substance entering the nucleus of intact cells is a significant hurdle for metastasis since there are at least three membrane barriers that prevent it: the nuclear membrane, the inner membrane, and the cell membrane. Fullerene's functional groups are connected to its very hydrophobic centre, which further complicates the behaviour of the molecule. By affixing hydrophilic moieties, fullerenes become water-soluble

and are capable of delivering medications and genes to cells. A peptide based on fullerene was developed by Thota et al. (2012), and its capacity to enter both flexed and unflexed skin was examined. In this work, porcine skin served as a model for human skin. Studies have demonstrated that mechanical bending alters the way the skin is organised structurally and increases penetration by weakening the epidermis' permeability barrier.

iv. Photosensitizers

Molecules that absorb light and transmit its energy to neighbouring molecules are known as photosensitizers. The photoelectric effect may be produced by electromagnetic radiation of any higher energy; this light frequently falls within the visible or infrared spectrum. By absorbing photons from incident light, photosensitizers can induce a ground-state electron into an excited singlet state. Intersystem crossover causes the excited singlet state electron to switch into its intrinsic spin state and become an excited triplet state electron (Moussa et al., 1997).

Using photoexcitation, fullerenes C_{60} can be aroused from their ground state. This short-lived species is easily converted into the long-lived C_{60} through intersystem crosses. Lu et al. (2015) used polyethylene glycol (PEG)-conjugated fullerene containing Gd^{3+} ions to show how photodynamic treatment can be used in conjunction with magnetic resonance imaging (MRI). The C_{60} -PEG of the photodynamic treatment photosensitizer contained MRI activity. Chelation and Gd^{3+} inclusion can change C_{60} -PEG compounds into photosensitizers with therapeutic and diagnostic capabilities.

v. Diagnostics

When a metal ion is inserted into a fullerene cage, endo-fullerene is formed. The isolation chamber made of an endohedral metallofullerene (EMF) cage can be employed to keep reactive atoms out of the living environment (Dorn & Fatouros, 2010). One rapidly expanding application of EMFs is the gadolinium-encapsulated endohedral metallofullerene (EMFs), which has been identified as one of the top prospects for next-generation magnetic resonance imaging (MRI) contrast agents (Amsharov & Merz, 2012). Additionally, metallofullerols are localised to macrophages in biodistribution studies, suggesting that these species are specifically targeted to tissues that are rich in macrophages and may be extremely beneficial chemotherapeutic agents for the treatment of leukaemia and bone cancer (Azzam & Domb, 2004). One of the derivatives $^{166}Ho^{3+}$ at $C_{82}(OH)_{30}$ has been extensively studied as a radioactive tracer for imaging diseased organs and killing cancer tumours. A carbon layer that is incredibly stable and resistant to human metabolism surrounds the radioactive element. Metal fullerenes that are not poisonous have been found. They can stay inside the body for nearly an hour and have the potential to photograph the circulatory system (Riedel & Dyakonov, 2004).

Photovoltaics

Fullerenes are widely used in artificial photosynthetic processes due to their high electron-accepting capacity and low reorganisation energy, which simplify electron transfer processes (Troshina et al., 2007). Due to its ability to construct donor-acceptor dyads with enough electron donor components to generate long-lasting charge-separated states, fullerene has found extensive utility in photovoltaic systems, organic electronics, and photocatalysis (Hayashi et al., 2004). Some organic and transition metal-containing electron-donating units that have been connected to fullerene cages include metalloporphyrins, cyanines, phthalocyanines, ruthenium

bipyridine complexes, boron-dipyrins, metallocenes, and tetrathiafulvalenes (Baby et al., 2011). According to research, the existing synergy between organic photovoltaics (OPVs) and organic field effect transistors is improving the performance of polymer transistors, such as organic field effect transistors (OFETs) and light detectors (OFETS). Since then, fullerenes have been used in photoelectric devices, electrochemical materials, conductive polymer films, gas sensors, and superconductors as doping impurities (Hayashi et al., 2004; Wang et al., 2015).

Fullerene-Based Polymeric Materials

Fullerene-based polymeric materials are created and then used in a variety of fields of endeavour due to their excellent electrical characteristics (Avent et al., 1997). Direct attachment of fullerene materials to polystyrene in Friedel-Crafts processes and indirect linking of fullerenes C_{60} with spacer groups like $Pt(dba)_2$, $Pd_2(dba)_3$, $CHCl_3$, or $Pt(cad)_2$ are two techniques to create fullerene-based polymeric materials. Insoluble PtC_{60} is formed when one of these spacer groups (where dba stands for dibenzylideneacetone and cad for cycloocta-1, 5-diene—reacts with fullerene C_{60} (Hayashi et al., 2004;)). However, in this case, they are typically formed or produced as polymer films on an electrode when C_{60} is reduced. These redox-active fullerene-based polymers can also be produced by the electrochemical reduction of fullerenes under cathodic conditions (Pyrzynska et al., 2007).

Water Purification/Environment

Despite the most abundant fullerene's (C_{60}) well-known photocatalytic capabilities and weak solubility in water, its limited stability in water is a significant drawback for uses in water purification and environmental protection. A material that can inactivate pathogenic germs by photocatalytic activities was found to be produced by functionalizing fullerene with hydrophilic moieties (Azzam & Domb, 2004). The study of the speciation of various metal forms has made advantage of fullerenes' capacity to act as adsorbents for organic molecules (Zhang et al., 2014). Aminofullerene and fullerols, photosynthetic fullerene derivatives, effectively produce reactive oxygen species (ROS), which may pave the way for the development of C_{60} -fullerene-mediated oxidation processes that might be extremely beneficial for water disinfection (Burakov et al., 2018).

Hydrogen Storage

Fullerenes can only store a maximum of 6.1% of hydrogen due to their molecular structure, which resembles a cage. It produces a weaker C-H bond than a C-C bond when hydrogenated. Because of this, when a substance is heated, the C-H bond breaks while still preserving the special structure of the Fullerene. This property makes fullerenes the perfect molecule for hydrogen storage. You may determine the degree of hydrogenation by looking at how this molecule's colour changes with increasing hydrogen intake, going from black to brown, then to red, orange, and pale yellow. This is because most hydrogen storage materials are dangerous and have poor storage capacities, fullerene hydrides have the potential to be used safely in the fuel cells of electric cars (Vidyaev et al., 2016).

Energy Materials

Surface electrodes for supercapacitors are commonly made of a conductive layer of carbon. Surface area, pore size distribution, accessibility to the electrolyte, and electrical conductivity are the main determinants of surface electrode capacitance (Lu et al., 2013). However, limited electrolyte accessibility to solid surfaces is frequently the root cause of low capacitance. As a result, to overcome the aforementioned inadequacies, nanotechnology has produced new potential through the utilisation of a variety of carbon-based nanomaterials (Nakamura & Isobe, 2003).

a. High-performance lithium-ion batteries

Due to carbon's higher safety and longer cycle life, materials based on carbon are used as anodes in lithium-ion batteries (Zhang et al., 2014). A team of scientists examined a high-performance anode material based on hydrogenated fullerenes for lithium-ion rechargeable batteries. According to study results, introducing hydrogenated fullerenes as additions to commercial graphite resulted in a startling fall in the carbon's irreversible capacity as well as an increase in its reversible capacity (Shen et al., 2013).

b. Superconductor materials

Studies have shown that when an alkali metal is inserted into the spaces of fullerene C₆₀, a new composite material is formed that converts into a superconductor (Wang et al., 2015). A high 3-D superconducting critical temperature, almost flawless 3-D superconductivity, current density, ductility, and outstanding stability have all been reported for the K₃C₆₀ composite in light of this (Kyesmen et al., 2016).

Reinforced Composites

It is widely acknowledged that enhancing the mechanical properties of materials used in infrastructure is effective when carbon-based nanoparticles are utilised as reinforcement (Lu et al., 2015). Fullerene C₆₀ has reportedly been used to reinforce Al-Mg alloy. The resulting aluminium-matrix composite has improved mechanical, thermal, and malleability properties (Nimibofa et al., 2018).

Summary

The molecule of fullerene is made up of rings with five to seven carbon atoms that are welded together by single and double bonds. The different types of fullerenes with numerous applications included buckminsterfullerene, nano-tubes, mega-tubes, nano-onions, and others. The study reveals two methods of synthesizing fullerene, with laser irradiation of PAHs being preferred over electric arc heating of graphite in most cases. They are crucial to the environment because of their advantages as sorbent materials, chromatographic stationary phases, and active micro-zones in sensors. Fullerenes and their derivatives have been used in medicine for various purposes, including antiviral, antibacterial, antioxidant, drug and gene delivery, photosensitizers, and diagnostic procedures. Particularly, fullerenes with additional function moieties have been applied to novel optical applications, non-invasive cancer imaging, and cancer therapy. Photovoltaics, polymeric materials, water purification/environment, hydrogen storage, energy storage, and reinforcement composites are some additional application areas. The introduction of functional moieties with high bioactivity to the fullerene molecule will

improve and increase its relevance in the pharmaceutical and chemical industries. Fullerenes have a wide range of applications, so it is important to find quick and inexpensive ways to make them and their derivatives. More work needs to be done on fullerene molecules, especially given how these molecules can be combined to create high-performing supramolecular assemblies and nanostructures for their specialized tasks.

Conclusion

Based on the findings of this study, fullerene and its derivatives could be used in the pharmaceutical sector as antiviral/antimicrobial agents, antioxidants, HIV protease inhibitors, and drug carriers for intracellular delivery. Since functionalization of the ring cage by addition or redox reaction to produce exohedral and endohedral adducts can make fullerene soluble, its insolubility in water and other polar solvents, which could have limited its variety of applications, is no longer a problem.

Fullerene now has other applications such as photovoltaics, polymeric materials, water purification, hydrogen storage, energy storage, and reinforced composites.

Suggestions

Fullerene is a viable compound open to a variety of synthetic processes. Thus, further research should be conducted on functionalized fullerenes in methane storage, catalysis, and environmental studies. Also more study should be considered particularly on the use of fullerene in supramolecular assemblies and nanostructures to improve performance in their respective fields of applications

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