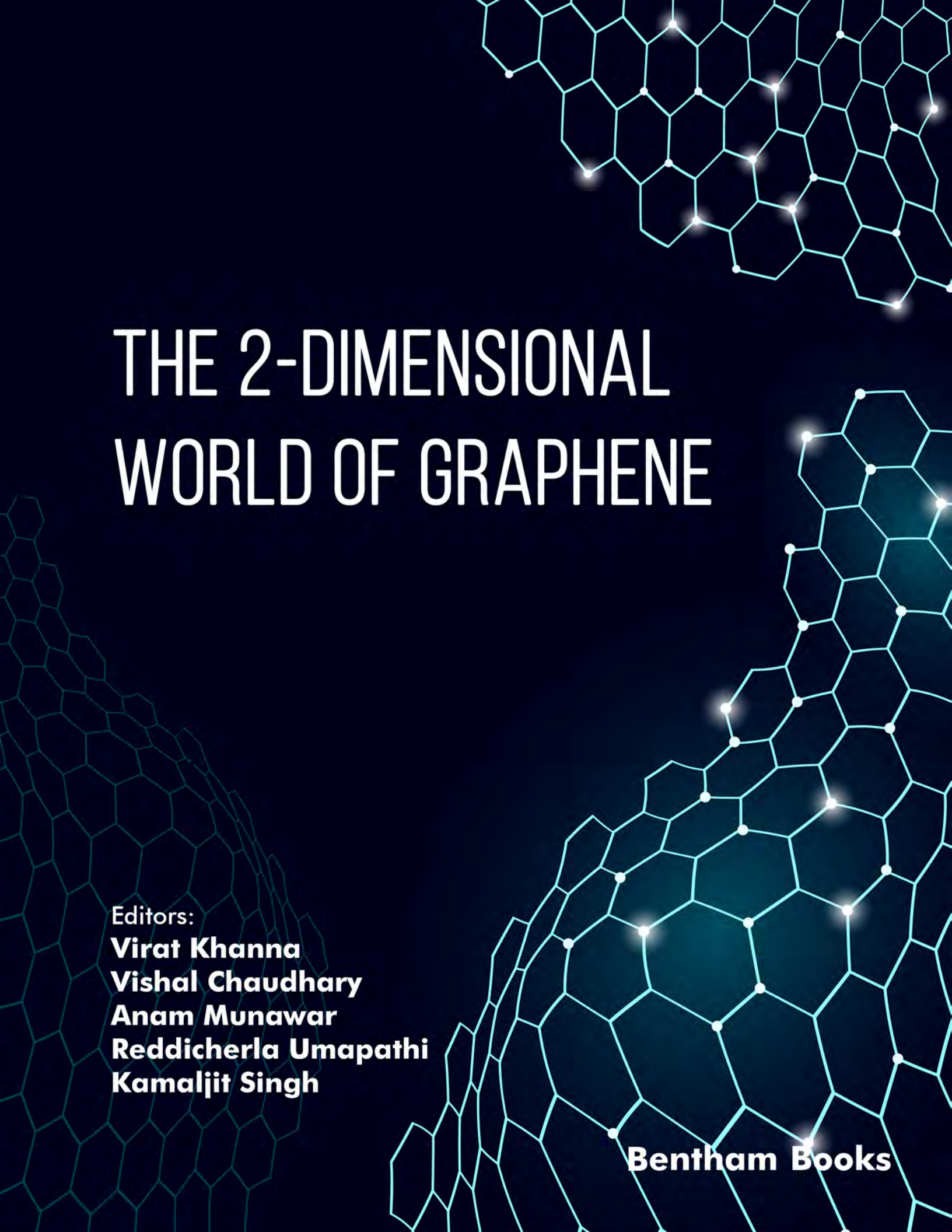

THE 2-DIMENSIONAL WORLD OF GRAPHENE

Editors:
Virat Khanna
Vishal Chaudhary
Anam Munawar
Reddicherla Umapathi
Kamaljit Singh

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The 2-Dimensional World of Graphene

Edited By

Virat Khanna
University Centre for Research & Development
Chandigarh University
Mohali, Punjab, India

Vishal Chaudhary
Department of Physics
Bhagini Nivedita College
University of Delhi, Delhi, India

Anam Munawar
Department of Forensic Medicine
University of Health Sciences
Lahore, Pakistan

Reddicherla Umapathi
Department of Biological Sciences and Bioengineering
Inha University, Incheon, Republic of Korea

&

Kamaljit Singh
Department of Mechanical Engineering
Chandigarh Engineering College
Jhanjeri, Mohali, India

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Editors: Virat Khanna, Vishal Chaudhary, Anam Munawar, Reddicherla Umapathi & Kamaljit Singh

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CONTENTS

PREFACE

The field of graphene research has flourished over the past decade, and it continues to captivate scientists, engineers, and innovators alike. Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, exhibits extraordinary properties that set it apart from conventional materials. Its exceptional electrical conductivity, thermal stability, and mechanical strength have paved the way for a myriad of groundbreaking applications.

The chapters featured in this book span a broad spectrum of topics, each exploring a unique facet of graphene's immense potential. Starting with the development of light energy converters, our contributors present a comparative analysis of short-chain dyad graphene oxide and graphene quantum dot nanocomposites—a critical step forward in harnessing renewable energy sources. Forensic applications take the center stage in the next chapter, where graphene-based nanomaterials demonstrate their prowess in enhancing forensic investigations, making a significant impact in the field of law enforcement and criminal justice. The global importance of water purification drives our attention to another chapter, which ingeniously showcases how graphene derived from solid waste materials can be a key player in tackling water contamination issues. Environmental consciousness remains a core theme as we delve into the green synthesis of reduced graphene oxide using agricultural waste—a compelling solution with immense potential for various environmental and health applications. Energy storage and conversion, essential components of the sustainable future we strive for, are eloquently discussed in the chapter dedicated to the synthesis, preparation, and properties of 2D graphene for electrochemical energy storage and conversion. Mechanical properties and structural integrity take precedence in the exploration of crack growth analysis of graphene nanocomposites, an essential aspect for ensuring the reliability of materials in various engineering applications. Finally, the impact of graphene on metal matrix composites is thoroughly examined, showcasing the enhancement of mechanical properties in these advanced materials.

Each chapter in this book represents a dedicated effort by the authors to contribute to the growing body of knowledge on graphene's potential. We are proud to say that this collection not only captures the current state of the field but also offers a glimpse into the exciting possibilities that lie ahead. We extend our heartfelt gratitude to all the authors who have passionately contributed their expertise, knowledge, and insights to make this book a reality. Their commitment to advancing scientific research has been pivotal in shaping the content of this publication.

We hope that "The 2-Dimensional World of Graphene" will ignite your curiosity, inspire further exploration, and spark new ideas that will drive the future of graphene research and its transformative applications.

Virat Khanna
University Centre for Research & Development
Chandigarh University
Mohali, Punjab, India

Vishal Chaudhary
Department of Physics
Bhagini Nivedita College
University of Delhi, Delhi, India

Anam Munawar
Department of Forensic Medicine
University of Health Sciences
Lahore, Pakistan

Reddicherla Umapathi
Department of Biological Sciences and Bioengineering
Inha University, Incheon, Republic of Korea

&

Kamaljit Singh
Department of Mechanical Engineering
Chandigarh Engineering College
Jhanjeri, Mohali, India

List of Contributors

Ahsan Riaz	Department of Forensic Medicine, University of Health Sciences, Lahore, Pakistan
Anam Munawar	Department of Forensic Medicine, University of Health Sciences, Lahore, Pakistan
Aquib Khan	Department of Polytechnic, Integral University, Lucknow, Uttar Pradesh, India
Abdul Shakoor	Department of Physics, University of the Punjab, Lahore, Pakistan
Bakht Mand Khan	Department of Applied Physical and Material Sciences, University of Swat, Rahim Yar Khan, KPK, Punjab, Pakistan
Behram Khan Ajat Khel	Department of Chemistry, Abdul Wali Khan University Mardan, Mardan, Pakistan
Che Azurahanim Che Abdullah	Biophysics Laboratory, Department of Physics, Faculty of Science, Universiti Putra Malaysia, Serdang, Selangor, Malaysia UPM-MAKNA Cancer Research Laboratory, Institute of Bioscience, Universiti Putra Malaysia, Serdang, Selangor, Malaysia Nanomaterials Synthesis and Characterisation Laboratory, Institute of Nanoscience and Nanotechnology, Universiti Putra Malaysia, Serdang, Selangor, Malaysia
Deepali P. Butala	Department of Chemistry, Sir Parshurambhau College, Pune, Maharashtra, India
Dharshini Perumal	Biophysics Laboratory, Department of Physics, Faculty of Science, Universiti Putra Malaysia, Serdang, Selangor, Malaysia
Emmellie Laura Albert	Nanomaterials Synthesis and Characterisation Laboratory, Institute of Nanoscience and Nanotechnology, Universiti Putra Malaysia, Serdang, Selangor, Malaysia
Faria Fatima	Department of Agriculture, IIAST, Integral University, Lucknow, Uttar Pradesh, India
Farah Hussain	Department of Physics, International Islamic University Islamabad, Islamabad, Pakistan
Ishani Mitra	Department of Physics, Jadavpur University, Jadavpur, Kolkata, India
Iqra Zafeer	Department of Forensic Medicine, University of Health Sciences, Lahore, Pakistan
Jamal Yousaf	Department of Physics, University of Wah, Wah Cantt, Wah, Pakistan
Kefayat Ullah	Department of Applied Physical and Material Sciences, University of Swat, Rahim Yar Khan, KPK, Punjab, Pakistan
Katyayani Mishra	Department of Biochemistry, Era University, Sarfarazganj, Lucknow, Uttar Pradesh, India
Khizra Arif	Department of Material Science and Engineering, Institute of Space Technology, Islamabad, Pakistan
Khansa Masood	Department of Physics, International Islamic University Islamabad, Islamabad, Pakistan

CHAPTER 1

Development of Light Energy Converters by using Short-Chain Dyad-Graphene Oxide and Graphene Quantum Dot Nanocomposites: A Comparative Approach

Ishani Mitra[1,*] and **Tapan Ganguly**[2]

[1] *Department of Physics, Jadavpur University, Jadavpur, Kolkata, India*

[2] *School of Laser Science and Engineering, Jadavpur University, Jadavpur, Kolkata, India*

Abstract: In this chapter, the measurements of fluorescence lifetimes of short-chain dyads ((E)-4-(((9H-fluorene-2-yl) Dimino)-methyl), N, N dimethyl-aniline (NND MBF)-graphene quantum dot (GQD) nanocomposite systems were made. The results observed from this system have been compared with the pristine dyad (p-dyad) and graphene oxide (GO)-dyad nanocomposite and Carbon Quantum Dot(CQD) nanocomposite. When compared to pristine dyad and dyad-GO systems, the dyad-GQD appears to be a much better light-energy converter because of its superior capacity for trans-conformer retention, which can occur even under a photoexcitation state. In the instance of the nanocomposite dyad NNDMBF-GQD, the surface trap effects may be the cause of the excited state's trans-conformer's relative stability when compared to its pristine form.

Keywords: Carbon quantum dots, Charge-separated species, Charge recombination, Electron transfer, Electron donor, Electron acceptor, Energy storage, Fluorescence lifetimes, Graphene quantum dots, Graphene oxide, Nanocomposites, Pristine dyad.

INTRODUCTION

The irrationality of a world with no energy, for even 10 minutes establishes the importance of its imprint in our daily life. Our world is subjugated to a violent storm of spiraling rates of chronic diseases, persistent infectious afflictions, and failures in public health. The emergence of a worldwide crisis and the overlap of the Covid-19 pandemic together with increasing chronic conditions like diabetes

[*] **Corresponding author Ishani Mitra:** Department of Physics, Jadavpur University, Jadavpur, Kolkata, India; E-mail: ishani19031991@gmail.com

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and obesity - with the environmental risks of global warming and air pollution - are taking their toll on human populations. We are living in a miraculous ecosystem, which is resilient and also fragile.

The urgency to realize a green alternative to fossil energy supplies has increased exponentially. This study involves artificial photosynthesis – a form of renewable energy sourcing that has been attempted for decades. The approach makes use of bio-mimetic techniques for replicating the natural photosynthesis process.

As society keeps advancing, there is an increasing need to develop renewable green energy as an alternative to the harmful energy standards that are prevalent. The continued use of conventional fossil fuel is depleting our natural resources and also emitting greenhouse gases that are hindering our environmental safety. Scientists have been exploring green alternatives that can lessen our reliance on the use of fossil fuels, covering almost 80% of the energy supply of our present world. Therefore, there are increased efforts to create high-tech energy systems inspired by Mother Nature herself. This involves artificial photosynthesis which mimics the biological reactions taking place within the natural plants, algae, and also certain bacteria which produce their energy and store this in chemical bonds.

During photosynthetic processes, photons provided by solar energy are initially absorbed by the chloroplasts, and chlorophyll pigments get arranged in protein environments. The protein-pigment complex elicits binding energy excitonic states by the absorption of photons that have been provided by solar energy. Multiple cascade levels of energy and photo-induced transfer of electrons processes, or PET, come next. Finally, the reaction center receives the electron energy to begin the chemical transition.

This classic instance from nature has motivated scientists in the designing of artificial light-harvesting systems by the use of nano-scale strategies. The improved understanding of the natural photosynthetic processes at molecular levels is assisted and inspired by the creation of artificial photosynthetic systems models, like the donor-acceptor assemblies. Major amounts of research work have been involved with developing artificial systems built with molecular and supra-molecular architecture, discussed in many relevant reviews.

In present times, renewable energy has sparked interest in designing artificial light energy conversion systems. More specifically, the synthesis of molecular photo electronic devices and the creation of molecular arrays are made to undergo electron transfer processes on photo excitation with the light of desired wavelengths.

Nanoparticles refer to microscopic particles with dimensions ranging from 1 to 100nm in size. Particles of this size have distinct chemical and physical characteristics that make them highly attractive for a variety of applications such as medicine, electronics, and energy, including environmental cleanup. Among the most notable advantages of nanoparticles is their high surface area: volume ratio, which allows for increased reactivity as well as effectiveness in a variety of applications. However, the small size of nanoparticles also presents potential risks to human health and the environment, as they can easily penetrate cell membranes and accumulate in organs. As such, careful consideration of their potential risks and benefits is essential in the development and use of nanoparticles.

Electron transfer studies on donor-spacer-acceptor molecule systems have opened up a new avenue for investigating the various features as well as advantages of electron transfer. Practical electron-transfer research in molecular DSA systems has permitted a thorough assessment regarding the Marcus electron-transfer framework and its extensions and predictions.

In recent times, nanocomposite materials, such as the carbon dots or the CDs and the metal nano-clusters or MNCs, are emerging as distinct classes of the newer generation of functional materials with unique abilities for acting as both the donor as well as acceptor moieties. Graphene is a well-known carbon allotrope. This name was introduced by Boehm, Setton, and Stumpp in 1994 [1]. It is a hexagonal lattice of carbon atoms organized in a monolayer. It comprises a two-dimensional substance made up of carbon atoms that have undergone sp2 hybridization. Its bond length (molecular) is 0.142 nm. It has attracted a lot of attention in recent years due to its unique electrical, optical, magnetic, thermal, and mechanical capabilities, as well as its enormous specific surface area. Because graphene is widely utilised in nanoelectronics, it is critical to generate high-quality graphene. By mechanically cleaving a graphite crystal, Geim, and Nosovelov were able to synthesise single layers of graphene in 2004.

Graphite is a material made up of stacked layers of graphene with an interplanar separation of 0.335 nm. Each of the layers of graphene within graphite is held together by Van der Waals forces, which are capable of being overcome *via* graphene exfoliation. In terms of thermal and electrical conductivity, graphite has a remarkable anisotropic behaviour. Additionally, graphene has some unique features that distinguish it from other carbon allotropes. It is around 100 times stronger than the strongest steel in terms of thickness, yet its density is far lower than any steel. This conducts heat and electricity very well and is practically translucent. It exhibits a huge and non-linear diamagnetism that is even greater than graphite and can be suspended by Nd-Fe-B magnets. It has extraordinary electronic, chemical, mechanical, thermal, and optical properties, making it a

CHAPTER 2

Graphene-Based Nanomaterials for Forensic Application

Ahsan Riaz[1,*], **Iqra Zafeer**[1] and **Anam Munawar**[1]

[1] *Department of Forensic Medicine, University of Health Sciences, Lahore, Pakistan*

Abstract: This chapter discusses the great potential of functional graphene-based nanosensors in forensic investigation. There are several limitations faced by forensic investigators in analyzing trace amounts of illicit drugs, narcotics, toxins, and explosives because of the sensitivity, specificity, selectivity, chemical and volatile nature of explosives, and impurities in the residues collected from the crime scene. This chapter highlights the application of functional graphene-based nanosensors and graphene quantum dots in improving forensic analysis by enhancing the sensitivity of these carbon-based nanoparticles and optimizing the response range of sensors. The major focus of this chapter will be on the application of graphene nanosensors for the detection of trace amounts of illicit drugs, narcotics, and explosives that are collected from crime scenes. It will also entail a comparison of the application of graphene nanoparticles and metallic nanoparticles for drug analysis.

Keywords: Mechanical and electromagnetic, Nanosensors, Nanotechnology, Optical.

INTRODUCTION

In order to provide vital information that will aid in the investigation of crimes, forensic studies depend on precise analytical techniques. Over the years, forensic testing has evolved and the focus is the on-spot testing as well as within forensic laboratory testing. Forensic testing precisely starts from the scene of a crime, where the forensic scientist looks for the evidence sample and their specific testing [1]. Crimes involving the use of illegal substances are very common; most of these crime scenes are associated with cocaine use as the preliminary drug. There are many on-spot color-based tests that look for the presence of cocaine in the crime scene environment. One of the most common on-spot tests is the Scott test based on the colorimetric principle of detection. The detection of cocaine is sometimes made difficult due to the existence of closely related interfering subs-

[*] **Corresponding author Ahsan Riaz:** Department of Forensic Medicine, University of Health Sciences, Lahore, Pakistan; E-mail: ahsinriaz555@gmail.com

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tances such as benzocaine, lidocaine, and procaine, making it difficult to identify and quantify. It is important to note that some compounds present in confiscated cocaine cause the Scott test to provide false positive results [2]. Fig. (**1**) shows the illustration of the typical detection of cocaine.

Fig. (1). Drug analysis for the detection of cocaine. Reprinted from [5].

Analytical techniques that are able to detect cocaine selectively include chromatography, spectroscopy, and electrophoresis as the principle of detection. These analytical techniques cause the precise detection of cocaine and other interfering substances are not detected in this way even when there are a large number of interfering substances. In truth, forensic scientists employ these techniques for confirmation analysis due to the heavy instruments; they cannot be used for in-field analysis or on-spot testing (preliminary test). Additionally, confirmatory studies are carried out in centralized labs and might take a few days before an illegal substance is confirmed or is destroyed over the time the sample is transported to the laboratory [3].

The introduction of electrochemical-based detection techniques has provided new and more advanced methods of detection. The analytical performance of the electrochemically sensing device is highly sensitive and selective towards the detection of the target analyte like cocaine. The precise sensing platform can determine the exact quantity of cocaine even in the contaminated samples, and the interfering substance. The electrochemically equipped devices are portable and can be transported to the crime scene for on-spot testing [4].

Electrochemical detection involves the use of working electrodes that cause the oxidation of cocaine and serve as the basis for its identification. Graphite, glassy carbon, and boron-doped diamond are examples of carbon-based electrodes. Conventional disc electrodes have also been used to illustrate electrodes that have undergone chemical modification, examples of the modification include the reduction of graphene oxide electrodes and the modification of platinum electrodes [6]. However, when it comes to mobility and inexpensive large-scale manufacture, miniature screen-printed electrodes are probably the best alternative. For this reason, some instances have been shown employing functional electrodes that haven't been altered chemically or otherwise. The sensitivity and selectivity of the electrode are due to its ability to isolate the specific peaks of cocaine from the other oxidation peaks that are caused by the closely relevant interfering substances. The electrochemical method frequently used for quantifying cocaine is mostly based on differential voltammetry principles [7].

Another modern-day sensing device is based on 3D technology; they have surely provided a great alternative to old bulky devices. The approach of 3D technology is based on fused deposition models (FDM). They are unique in their processing like flexibility in their designs, limited use of energy, quick generation of prototyping response, and highly economical. 3D printing technology is becoming more and more common in various fields of science and engineering (functional in remote areas) [8]. It is utilized as electrochemical sensors and storage-based devices; 3D printing has proved beneficial to the fields of analytical chemistry and electrochemistry. In light of the forensic scenario, 3D-printed instruments have been utilized in crime scene testing involving explosive materials. Their abilities for sensing and detecting explosives of nitro origin and gunshot residues are reported. At present, they have very limited abilities for the detection of illegal drugs associated with criminal cases [9].

Due to its distinctive physicochemical characteristics, the two-dimensional, honeycomb-structured, single-carbon layered graphene has been widely exploited in the sensor-detecting industry. Graphene has gained its remarkable future due to its outstanding features like the existence of a larger surface area, increased mechanical strength, increased electrical conduction; high electron mobility, adjustable optical characteristics, room temperature quantum Hall effect, and simplicity of functionalization, making it an ideal nanomaterial for the construction of sensors [10]. Due to this, a wide range of very sensitive sensors, including colorimetric, electrochemical, potentiometric, fluorescence-based, *etc.*, may now be made [11].

CHAPTER 3

Graphene from Solid Waste Materials for Water Purification

Shobha Waghmode[1,*] and **Deepali P. Butala**[2]

[1] *Department of Chemistry, MES Abasaheb Garware College, Pune, Maharashtra, India*

[2] *Department of Chemistry, Sir Parshurambhau College, Pune, Maharashtra, India*

Abstract: Graphene is both the thinnest and the lightest material studied by the scientists. Amongst the various applications of graphene, water purification is the major one. Originally graphene was prepared using graphite and other hydrocarbons as precursors. Recently waste materials like rice husk, hemp, paper cups, and other biomass have been used as graphene precursors. Similarly, graphene can be synthesized from plastic wastes like PET (polyethylene terephthalate) bottles waste as a source material and polyethylene(PE) and polypropylene(PP) as a carbon source.

Water is required by human beings for living, house chores, and industrial processes. Waste water treatment is an essential topic related to human health and industrial uses. Water pollutants are mainly divided into two types; organic water pollutants and inorganic water pollutants. The organic water pollutants are dyes, pharmaceuticals, fertilizers, pesticides, herbicides, polycyclic aromatic hydrocarbons, *etc.* Inorganic water pollutants are rare earth elements like La, Ce, Ho, Eu, and Y, other organo-metallic catalysts, and fertilizers containing heavy metals. Waste water treatment processes are essential to eliminate or decrease pollutants and provide a safe water supply. Study shows that graphene and graphene oxide are promising materials for eliminating pollutants from water.

Keywords: Graphene, Graphene oxide, Industrial waste, Microbial pollutants, Inorganic pollutants, Organic pollutants, Plastic waste, Synthesis, Solid waste, Water pollution.

INTRODUCTION

Graphene is a material containing carbon atoms positioned in a hexagonal fashion. It is two-two-dimensional sp2 hybridized single-layered sheet of graphite having honeycomb-like structure. One millimeter of graphite will have millions of layers of graphene [1]. Graphene is the strongest and thinnest material known to

* **Corresponding author Shobha Waghmode:** Department of Chemistry, MES Abasaheb Garware College, Pune, Maharashtra, India; E-mail: saw.agc@mespune.in

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date. It is two hundred times stronger than steel. Graphene is the most reactive form of carbon extremely light-weight and ultrathin material. It is the hardest material and has high electrical and thermal conductivity. The tensile strength is higher than the order of 130 Gpa. It is an optically transparent, flat, and flexible material.

Initially, defect-free graphene was prepared through mechanical exfoliation, and its properties were studied, which led to some unconventional properties of the graphene-like the quantum hall effect, Dirac Fermion behaviours, exceptional mechanical stiffness, and absence of weak localisations in electronic structure [2]. The thermal conductivity of graphene is measured to be as high as 5300 W/m/K and has excellent structural stability at this high temperature.

GO and multilayer GO could be prepared from the oxidation of graphite by using fuming nitric acid, sulphuric acid, and other oxidising agents *i.e.* by modified Hummers Method or other methods. The reduction of graphene oxide gives graphene. The compound GO *i.e.* graphene oxide has chemical formulae, C_8 O_2 $(OH)_2$ [2].

Graphene (Fig. **1**) is a lighter material with a planar density of 0.77mg/m^2. The structural unit of graphene is a hexagon with a surface area equal to 0.052 nm^2.

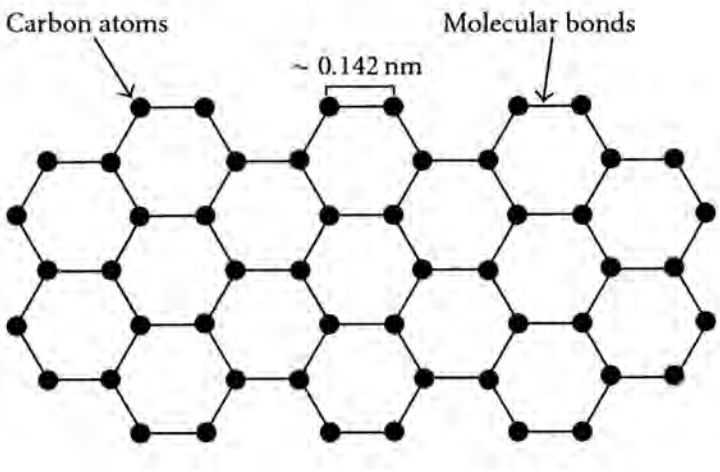

Fig. (1). Structure of graphene.

SOLID WASTE

The term solid waste is used for artificial waste containing mainly plastic garbage disposed in the environment. This plastic either floats on the water surface or may

go to the bottom. It accumulates due to human waste disposal on the street, then discharged into river waters or sea. This waste is carried in the water as a pollutant and finally mixed and accumulates in the sea. For our study purpose, solid waste can be broadly classified into three groups; plastic waste, agricultural waste, and other waste. We will see each type one by one in detail.

Plastic Wastes

The world's plastic production is increasing tremendously day by day. In 2019, the world's plastic production was over 370 million metric tonnes. Recent calculations show that the world's plastic waste will reach 25,000 million metric tonnes by 2050. This enormous production and utilization of plastic for improving standards of life have ill effects on the environment due to its non-decomposable nature. Plastic waste management is a challenge for the scientific community [3]. Among the available plastic, about 36.4% would be thrown back into the environment or landfills, almost 36.4% would be incinerated and only about 27.2% would be recycled. Thus the soil, and water resources *i.e.* fresh water and seas are getting infected by the plastic wastes which in turn leads to damage to terrestrial and aquatic flora and fauna. The steps to minimize the plastic waste in the environment and reduce its effect on living beings will help control the global plastic waste crisis. The main hindrance to recycling plastic waste is the lack of economically profitable by-products [4].

Using plastic waste as a raw material for the synthesis of value-added products is considered to be the motivation for plastic recycling [5]. Solid plastic waste can be used as raw material for the preparation of graphene nano-sheets. It has been experimented that polyethylene, polypropylene, and polystyrene act as efficient precursors for the synthesis of carbon nanomaterials including carbon nanotubes, carbon spheres, carbon nano-fibres, and graphene nano-sheets.

There has been increasing interest in the conversion of waste plastic into carbon materials as carbon materials have many unique properties [6].

Agro-Waste

Raw biomass and agro-waste are huge and cheap sources of carbon for the preparation of value-added carbon material. The conversion of biomass into carbonaceous material is being studied intensely for the commercial production of graphene-based material [7]. Until now successful synthesis of graphene-based materials starting from biomass or agro-waste like rice husk, paper cups, hemp, foodstuffs, and even insects have been carried out [7]. Biomass can be used as a raw material for the production of carbon material as it is an environment-friendly renewable resource [8].

CHAPTER 4

Importance of Graphene in Energy Storage and Production Devices

Bakht Mand Khan[1], Reshma Wadood[1], Won Chun Oh[2] and **Kefayat Ullah[1,*]**

[1] *Department of Applied Physical and Material Sciences, University of Swat, Rahim Yar Khan, KPK, Punjab, Pakistan*

[2] *Department of Advanced Materials Science & Engineering, Hanseo University, Seosan-si, Republic of Korea*

Abstract: Graphene, a 2D material with outstanding electrical, optical, and mechanical properties, has attracted scientists and researchers globally, to design and fabricate various graphene-based energy production and storage devices. The influence of graphene was found to improve the performance and cyclability of many energy production and storage devices. In this chapter, we highlighted the structure, synthesis, and importance of graphene and its utilization in various energy-related technologies.

Keywords: Anode, Batteries, CVD, Catalysis, Electrodes, Energy storage, Functionalization, Fuel cells, Graphene, GO, RGO, Hydrogen production, Lithium ion, Nanomaterials, Photocatalysis, Pyrolysis, Solar cells, Semiconductor, Supercapacitors, TMOs.

INTRODUCTION

Carbon is considered one of the most abundant materials on Earth. In the previous decades, carbon derivatives have been found to be the most fascinating materials, which play an important role in modern technology [1, 2]. Carbon is one of the most fundamental elements in our universe, having a number of allotropes with many unique characteristics [3]. In 2004, two scientists Geim and Novoselov, applied the Scotch Tape method to effectively separate graphene from graphite. In 2010, this discovery was rewarded with a Nobel Prize in physics, which resulted in a significant increase in study into this new unique material [4, 5]. The discovery of graphene has attracted widespread interest in different sectors of current nanomaterial technology, owing to the fact that most of its characteristics differ from those of graphite, which has major applications in various fields [6].

[*] **Corresponding author Kefayat Ullah:** Department of Applied Physical and Material Sciences, University of Swat, Rahim Yar Khan, KPK, Punjab, Pakistan; Tel: +92946-881795, +923459207686, E-mail: kefsayed@uswat.edu.pk

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High-frequency devices, optoelectronics, spintronics, sensors, photocatalysis, medicinal equipment, superconductors, solar panels, battery electrodes, electric automobiles, fuel cells, *etc.* have already been utilizing graphene or graphene derivatives with improved electrical and mechanical properties [2, 7 - 9]. Overall, the unique properties of graphene make it a promising material for the development of more efficient and sustainable energy storage and production devices. In this chapter, we mainly highlighted the structure, properties and various applications of graphene in energy-related devices such as supercapacitors, Li-ion batteries, fuel cells, solar cells and photocatalytic hydrogen production.

STRUCTURE AND PROPERTIES OF GRAPHENE

Graphene is an allotropic form of carbon that consists of a single layer of carbon atoms arranged in a honeycomb lattice structure with the length of carbon bonded atoms being 0.142nm [10]. Carbon atoms are arranged in sp^2 hybrid orbitals in graphene, providing a hexagonal lattice structure (honeycomb) [11, 12]. The pi (π) electrons of graphene are responsible for its high conductivity. There are total six electrons in a carbon atom and its valence shell contain four valence electrons. Three from the total four valence electrons form a bond with other carbon atoms in a two-dimensional graphene hexagonal structure, while the fourth electron may travel freely in the 3D space [13]. The π bond is responsible for the graphene electronic and electrical conductivity. The graphene lattice is made up of unit cells with two carbon atoms separated by 1.42Å and an interplane spacing of about 3.4 Å [14].

Graphene is regarded as the mother of all other graphitic forms of carbon atoms because of its excellent properties and structure [15]. Graphene is rolled to one dimensional cylinder of allotropes of carbon called carbon nanotubes and zero dimensional buckyball (fullerene) can be obtained by wrapping the sheet of graphene. Stacking varying numbers of sheets of graphene together results in monolayer graphene, few layer graphene and graphite (Three dimensional allotrope of carbon) [16].

Single or monolayer graphene is made up of one graphitic layer, bilayer graphene is made up of two layers, trilayer graphene is made up of three layers of graphite stacked together and few layer graphene (FLG) is made up of five to ten graphitic layers, while multi-layer graphene (MLG) is made up of around twenty to thirty graphitic layers [17]. The number of layers is highly significant in electronic/electrical and optical applications, the optical absorption and electrical resistance of graphene depends on the numbers of layers. In a visible region, graphene with one to five layers (few layers' graphene) reflects just <0.1 percent

of incident light. This increases to ~two percent for ten layers (multi-layers' graphene), whereas electrical resistance reduces as the number of layers increases [18].

Graphene is regarded as one of the thinnest materials of universe, with the dimension of single carbon atom about 0.34 nm. However, graphene is considered the strongest material, exceeding diamond and steel. Graphene is also one of the lightest materials (lighter than paper) [19]. In aspects of thickness, it means that 1mm of graphene may be obtained by stacking million sheets of paper [20]. Graphene is harder than diamond and a good thermal conductor than diamond. Also, it is three hundred (300) times stronger than steel. Due to these properties, graphene is regarded as the most significant material in the next century [21]. It has outstanding properties containing exceptional thermal conductivity of about 5000 W m^{-1} K^{-1}). Transparency to visible light is quite high (97.7%), with high carrier mobility of approximately 200 000 cm^2 V^{-1} s^{-1}, ambipolar electric field effect, and large surface area (2630 m^2 g^{-1}) [22]. Graphene's unique structure contributes to a variety of interesting characteristics, including large mechanical strength having tensile strength about 130 GPa and Young's modulus about 1 TPa [15], having a lower density of 1.06 g/cm^3 [23]. Fracture strain and high stiffness make it a potential choice for the industrial sector such as paints, bio applications and nanocomposite coatings [24]. In terms of chemical characteristics, graphene has a very good chemical stability [25]. Graphene has large electrical conductivity of 1738 S/m, extremely good bending capabilities and good thermal stability, which make them ideal for many applications such as transparent, flexible electrodes, conducting electrodes and opto-electronic devices because of its good optical transparency [26].

Graphene has a zero band gap, which means that its band structure is linearly dispersed as well as the charge carriers behave as massless Dirac fermions in a particular k-point in first Brillouin zone [27]. Because of its zero band gap, it absorbs light in a wide variety of spectra ranging from infrared to ultraviolet, allowing it to be used in electro-optical systems/devices [28]. In the overlapped conduction and valence band, graphene behaves as zero-gap semiconductor with large carrier mobility at the speed of ~106 m s^{-1} (relativistic speed) [29, 30].

Graphene provides sufficient empty space to compensate for volume changes when ions are repeatedly inserted or extracted, and it strengthens the contact area of electrolyte/electrode to increase the capacity of electro-chemical energy storage devices [31, 32]. Graphene has been considered a promising two-dimensional material for the spintronics due to its prolonged relaxation time of spin [33]. Graphene is an excellent option for surface reactions due its high specific surface-area having a large theoretical value (2630 m^2g^{-1}) [34]. Graphene has unique 2D

CHAPTER 5

Green Synthesis of Reduced Graphene Oxide Utilizing Agricultural Waste and Nanocomposite for Potential Environmental and Health Applications

Dharshini Perumal[1], Che Azurahanim Che Abdullah[1,2,3,*] and **Emmellie Laura Albert[3]**

[1] *Biophysics Laboratory, Department of Physics, Faculty of Science, Universiti Putra Malaysia, Serdang, Selangor, Malaysia*

[2] *UPM-MAKNA Cancer Research Laboratory, Institute of Bioscience, Universiti Putra Malaysia, Serdang, Selangor, Malaysia*

[3] *Nanomaterials Synthesis and Characterisation Laboratory, Institute of Nanoscience and Nanotechnology, Universiti Putra Malaysia, Serdang, Selangor, Malaysia*

Abstract: Carbon-based technology has become a multidisciplinary field including water treatment, agriculture, material science, medicine, and other sciences due to their unique characteristics. Research on graphene technology has focused heavily on graphene and its derivatives, including graphene oxide (GO) and reduced graphene oxide (rGO). Traditional processes for producing rGO involve harsh conditions, including high temperatures and hazardous chemicals and solvents. The creation of green-based nanomaterials is the current research focus on a global scale. Nanotechnological applications are rapidly growing that use agricultural waste biomass as a reducing agent and turn it into graphene-based products in an effort to lessen their detrimental effects on the environment. Graphene-based materials and metal nanoparticles are frequently combined to improve the characteristics of nanomaterials today with the use of green reductants. Additionally, rGO not only offers the nucleation site but also prevents metal nanoparticles from clumping together. Here, we discuss the utilization of agricultural waste biomass for green rGO production and graphene-based metal nanocomposite, as well as its application to the environment and healthcare. Finally, this review offers some insight into potential future developments, particularly with regard to scaling up rGO and graphene-based metal nanocomposites in many potential applications.

[*] **Corresponding author Che Azurahanim Che Abdullah:** Biophysics Laboratory, Department of Physics, Faculty of Science, Universiti Putra Malaysia, Serdang, Selangor, Malaysia, UPM-MAKNA Cancer Research Laboratory, Institute of Bioscience, Universiti Putra Malaysia, Serdang, Selangor, Malaysia and Nanomaterials Synthesis and Characterisation Laboratory, Institute of Nanoscience and Nanotechnology, Universiti Putra Malaysia, Serdang, Selangor, Malaysia; E-mail: azurahanim@upm.edu.my

Virat Khanna, Vishal Chaudhary, Anam Munawar, Reddicherla Umapathi and Kamaljit Singh (Eds.)

Keywords: Biomass, Graphene oxide, Green, Metal nanoparticles, Reduced graphene oxide.

INTRODUCTION

A new and rising area of contemporary material science is nanotechnology. There are many growing concerns among academics due to the advancement of nanotechnology. This inspires them to find a solution to the problems that arise. It includes sectors in agriculture, water treatment, medicine, and others [1]. Nanotechnology integrating nanoparticles enhances the potential of the material utilized in various applications. Nanoparticles (NPs) are particles that are less than 100 nm in size [2]. It is possible to categorize NPs using their size, shape, and physicochemical properties. Lipid-based, carbon-based, ceramic, metal-based, polymer and semiconducting NPs are among their components [3].

Carbon NPs can transform into a variety of allotropes, including graphite, graphene, fullerenes, and carbon nanotubes. Graphene derivatives, graphene oxide (GO) and reduced graphene oxide (rGO) have exceptional physicochemical characteristics and distinctive morphological structures [4]. rGO has gained attention due to its huge surface area, excellent electrical conductivity, chemical stability, and mechanical strength [5]. These characteristics led to the usage of rGO in various applications, as shown in Fig. (**1**). Conventional methods for producing rGO include the use of chemical reductants that yield hazardous by-products. The aforementioned processes encompass oxidation, carbonisation, pyrolysis, and the presence of hazardous chemicals. Eco-friendly preparation of quality rGO is expanding in the field of graphene technology. Due to its environmentally safe nature, cost-effectiveness, and sustainability, the green method utilizes microorganisms, plant extracts, biomass, and biomolecules [6, 7].

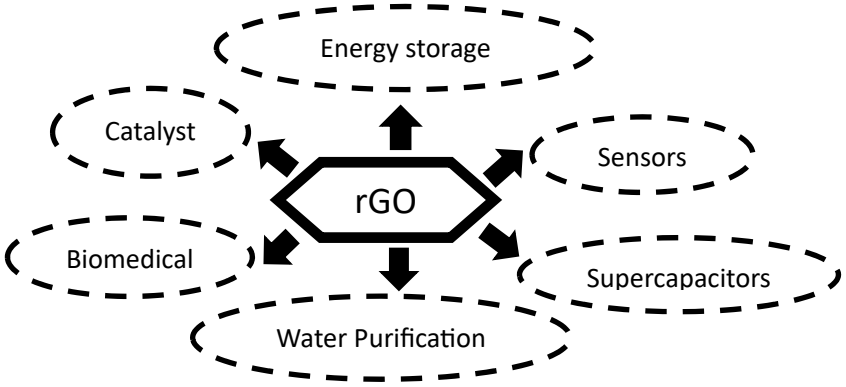

Fig. (1). Diagram of rGO applications.

Recently, graphene-based metal nanocomposite has generated a lot of interest in their synthesis. As a result of their remarkable mechanical, optical, catalytic, and electrical characteristics [8], nanocomposites have great promise for enhancing sensitivity and stability. They have high adsorption, quick electron transfer, and superior biocompatibility [9]. Graphene-based material serves as a substrate for immobilization, while metal NPs initiate free radical reactions [10]. They have potential usage in various applications as sensors, catalysts, and biological agents [11, 12]. This chapter includes a brief review of the synthesis of rGO from agricultural waste and graphene-based metal nanocomposites, as well as details on their applications.

GRAPHENE-BASED NANOPARTICLES

Graphene

Graphene, an allotrope of carbon, is the thinnest 2D nanomaterial discovered [13]. The atoms of carbon are arranged in a single layer, forming a hexagonal crystalline structure. The special configuration gives graphene a huge surface area, good mechanical strength, flexibility, and superior thermal and electrical conductivity [14]. Novoselov and co-workers used Scotch tape to exfoliate graphene for the first time [15]. There are several techniques for making graphene. This includes chemical vapor deposition, chemical exfoliation, mechanical cleaving, and thermal, and chemical reduction of GO [16, 17].

Despite its unique properties, its hydrophobic nature and strong propensity to aggregate (caused by the Van der Waals interaction) have reduced its applications [18]. Alternatively, graphene-like compounds can be produced from graphite or other carbon sources. Numerous benefits of the pristine graphene can be obtained while introducing the surface with oxygen functional groups. The result of oxidising graphite in a protonated solvent is graphite oxide, which is made up of several layers of graphene oxide (GO) [19].

Graphene Oxide (GO)

Graphite is often treated chemically by oxidation and subsequently, exfoliation to form GO, which is just one layer (Fig. **2**) [17]. GO could be generated by the oxidation of graphite through several approaches, including Brodie’s, Staudenmaier’s, and Hummer’s method [20]. Exploring the reactivity of flaky graphite in 1859, British chemist B. C. Brodie made the first effort to make graphite oxide [21]. Later, in 1898, L. Staudenmaier enhanced Brodie's method by proposing a less risky and challenging method for GO creation [22]. The technique developed by Hummers and Offeman in 1958 is the most important and widely used technique for producing graphite oxide [23]. In general, all of the

CHAPTER 6

Graphene Nanoparticles: Technological Concepts and Future Applications

Manaal Zahera[1], Aquib Khan[2], Katyayani Mishra[3] and **Faria Fatima[4,*]**

[1] *Department of Biotechnology, Era University, Sarfarazganj, Lucknow, Uttar Pradesh, India*

[2] *Department of Polytechnic, Integral University, Lucknow, Uttar Pradesh, India*

[3] *Department of Biochemistry, Era University, Sarfarazganj, Lucknow, Uttar Pradesh, India*

[4] *Department of Agriculture, IIAST, Integral University, Lucknow, Uttar Pradesh, India*

Abstract: Graphene, one of the most recent materials, has unique physical and chemical properties. The low weight and honeycomb structure of graphene gives it extraordinary unique properties. According to a recent study, experts from many different disciplines, such as biological science, energy, and the environment, are interested in graphene-based composites. These nanoparticles also show certain biologically undesirable effects that need to be clarified. As a result, it became important to analyse graphene's characteristics and potential uses. In this chapter, recent advancements in the synthesis process for composites consisting of nanoparticles and graphene, examine their properties and discuss their advantages for a variety of applications. Additionally, the important properties of the unit cell's edges, bond formation, bond electronic structure, and stacking sequence were emphasized. Investigations are also conducted into how these illnesses affect the thermal, electrical, mechanical, and chemical characteristics of graphene. Following a brief explanation of the fundamental composition, production methods, and their properties are discussed. Finally, present challenges in surface modification are explored, along with prospective directions for future study. Thus this paper detailing the excellent techniques and some cutting-edge graphene applications is necessary.

Keywords: Biomedical, Construction, Graphene, Medical, Magnetic, Manufacturing.

INTRODUCTION

The strength, flexibility, lightness, and resistance of graphene are noteworthy. This substance is thought to be five times lighter and 200 times more resistant than steel. The fields of energy, building, health, and electronics may all benefit

* **Corresponding author Faria Fatima:** Department of Agriculture, IIAST, Integral University, Lucknow, Uttar Pradesh, India; E-mail: fatimafaria45@gmail.com

Virat Khanna, Vishal Chaudhary, Anam Munawar, Reddicherla Umapathi and Kamaljit Singh (Eds.)

from graphene's advantages [1]. Carbon is the strongest, thinnest, and most electrically and thermally conductive material in the universe. Nippon Electric Company (NEC) Ltd. published the first study on carbon nanotubes and the growth of the family of carbon materials in 1991. Micro-computer scraping was used to remove graphene from its monolithic state, defying the two-dimensional crystalline theory [2]. It is a two-dimensional carbonaceous material with a hexagonal honeycomb crystal structure. Graphene is currently the thinnest nanomaterial, having a thickness of 0.34 nm. Each carbon is joined to three other C atoms. With a C-C bond length of about 0.142 nm, graphene has a remarkably stable structure. Graphene has a very strong connection between each carbon atom. The atomic surface within graphene deforms and bends when an external force is applied to it in order to counteract it. As a result, the carbon atoms do not rearrange or go out of alignment, creating a constantly stable structure [3]. When graphene electrons move in the internal orbit, there is no scattering effect caused by the interference of external atoms or lattice flaws. The exceptional qualities of graphene are a result of its unusual lattice structure. Today, there are several ways to make graphene, but the four most common ones are chemical vapour deposition, liquid phase stripping, mechanical stripping, and epitaxial growth. Recent years have seen significant studies on graphene quantum dots (GQD) and carbon doped with other elements, chemicals, or organic compounds. The scientific community has taken a keen interest in graphene due to its extraordinary mechanical, physical, and thermal characteristics. A number of preparation techniques for graphene have been created recently. It has several uses in numerous industries as a result of its fascinating features.

MANUFACTURING PROCESS

Various methods have been developed for producing graphene, such as chemical vapor deposition (CVD)/chemical vapor transport (CVT), conversion of SiC, reduction of GO, chemical/liquid/solid/gas/mechanical exfoliation of graphite, and laser-assisted manufacturing.

Chemical Vapor Deposition/Chemical Vapor Transport (CVT) Method

The most widely used method, CVD, has a lower yield and higher cost but can produce high-quality graphene with superior layer control, including single crystals. The most popular method of bulk preparation involves physically or electrochemically exfoliating graphite, either with or without a solvent. Chemical exfoliation may be produced by oxidizing GO, and subsequent reduction produces an FLG, that processes damaged graphene planes. Although bottom-up synthesis can employ tiny halogenated molecules as precursors to create graphene with well-defined structures and properties, the scales are too small for practical usage

[4] (Fig. **1**). Although simple exfoliation is hindered by the high vdW energy of micron-scale materials, the peculiar 2D nature typically necessitates nano dispersion into monolayers. Two extra steps should be considered while performing liquid exfoliation procedures: (i) decreasing layer-layer contact by increasing the interlayer spacing, and (ii) physical agitation for dispersion. In 1958, it was demonstrated that the oxidation of graphite, sometimes known as "graphite oxide," could increase the interlayer distance from 3.4 to 7.0. The interlayer gap was widened, which made it possible to sonicate the individual graphite oxide layers and distribute them. Then, using reducing agents and heat annealing, graphite oxide layers may be chemically reduced to graphene nanosheets. Liquid exfoliation enables the scalable synthesis of 2D nanosheets at an ambient temperature and atmospheric pressure. This approach, however, leads to non-uniform nanosheet thickness and therefore preventable damage.

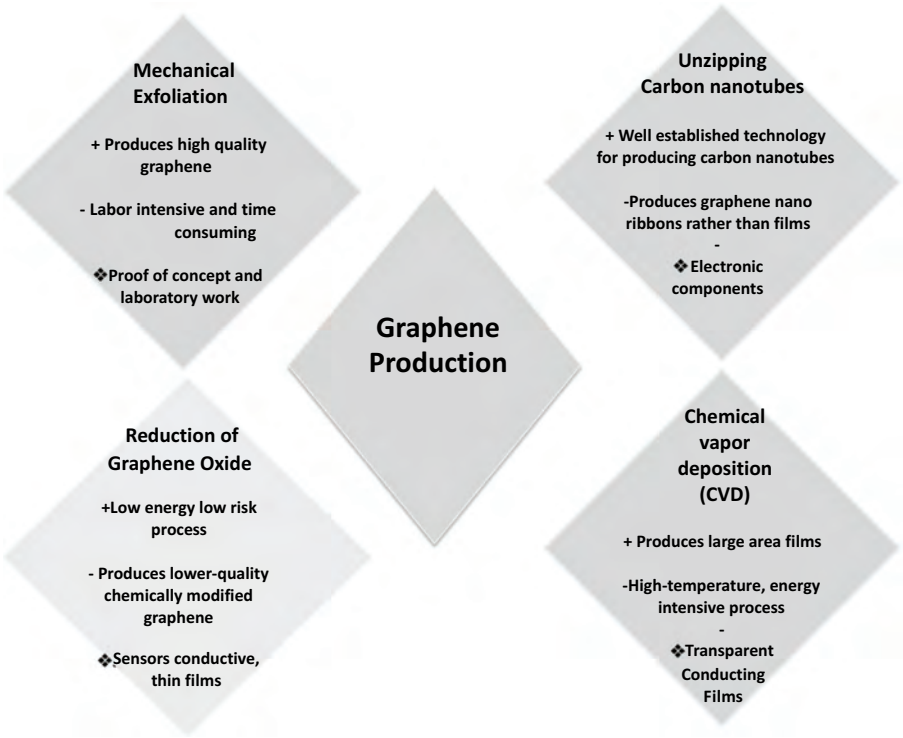

Fig. (1). Mode of synthesis.

Wet Chemical Synthesis Method

The hydrothermal/solvothermal synthesis processes, in which compounds are dissolved in an organic solvent or an aqueous solution under high vapour pressure

CHAPTER 7

Synthesis, Preparation, and Properties of 2D-Graphene for Electrochemical Energy Storage and Conversion

Abdul Shakoor[1,*], Rabia Siddiqui[2,*], Malika Rani[2], Khizra Arif[3], Marvi Dashi[4], Muhammad Faiz Junaid[5], Jamal Yousaf[6], Muhammad Atif[7], Muhammad Awais[8], Behram Khan Ajat Khel[9] and **Muhammad Waseem[10]**

[1] *Department of Physics, University of the Punjab, Lahore, Pakistan*

[2] *Department of Physics, The Women University Multan, Multan, Pakistan*

[3] *Department of Material Science and Engineering, Institute of Space Technology, Islamabad, Pakistan*

[4] *Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan*

[5] *Department of Physics, University of Agriculture Faisalabad, Faisalabad, Pakistan*

[6] *Department of Physics, University of Wah, Wah Cantt, Wah, Pakistan*

[7] *Institute of Metallurgy and Materials Engineering, University of the Punjab, Lahore, Pakistan*

[8] *Department of Physics, COMSATS, Islamabad, Pakistan*

[9] *Department of Chemistry, Abdul Wali Khan University Mardan, Mardan, Pakistan*

[10] *Centre of Excellence in Solid State Physics, University of the Punjab, Lahore, Pakistan*

Abstract: Stimulating properties of two 2D-Graphene, like its huge surface area, exceptional electrical conductivity, extreme thinness, amazing electron kinesis, and state-of-the-art mechanical regulation, have added an enormous investigative concern. This background exhibits significant dynamism and find widespread application in various energy storage devices like Li-sulfur batteries, Li-ion batteries, Li-oxygen batteries, sodium Ion batteries and also as a hybrid cathode/anode material for supercapacitors. Scaled-up, stable production and correspondence of carbon-based nano-materials are essential conditions for the preparation of graphene-based EESDs. This chapter diagnostically explains the synthesis methods of graphene and the properties of graphene-nanomaterials with various dimensions in adaptable EESDs. The main tasks and scenarios in this field are also discussed.

Keywords: Energy storage, Electrochemical, Graphene, Sustainable development.

[*] **Corresponding authors Abdul Shakoor and Rabia Siddiqui:** Department of Physics, University of the Punjab, Lahore, Pakistan and Department of Physics, The Women University Multan, Multan, Pakistan;
E-mails: abdulphysics2020@gmail.com and rabiasiddiqui786@gmail.com

Virat Khanna, Vishal Chaudhary, Anam Munawar, Reddicherla Umapathi and Kamaljit Singh (Eds.)

INTRODUCTION

Our world is undergoing rapid transformations, and along with them, our energy requirements are evolving as well. As the global population continues to grow at an unprecedented rate and economies expand rapidly, there arises an urgent demand for clean and sustainable energy sources. This imperative goes beyond mere fulfillment of increasing energy needs; it also serves to combat pollution, mitigate global warming, and safeguard against the consumption of fossil fuels [1, 2]. The encouraging news is that we are actively engaged in the development of novel energy conversion and storage technologies, like fuel cells, solar cells, and batteries. The performance of these devices hinges significantly on the materials employed, prompting dedicated scientific efforts toward the creation of fresh nanomaterials endowed with favorable nanostructures and extensive surface/interface areas [3, 4].

Of particular note, carbon nanomaterials have emerged as highly promising contenders within the energy sector. We invite you to embark with us on an exploration of the dynamic domain of clean and renewable energy and to delve into the pivotal role that carbon nanomaterials are poised to assume in shaping our future.

The molecular structure we are examining has various shapes, as shown in Fig. (**1**). The first shape is like tiny spheres called fullerenes, which we call a 0D structure because it does not extend in any direction. The second shape is like long, rolled-up tubes called carbon nanotubes, and we call this a 1D structure because it extends in one direction. The third shape is a single, flat sheet of atoms known as graphene, and we consider it a 2D structure because it's like a flat surface. The fourth shape is a big, stacked structure called graphite, and we call it a 3D structure because it extends in three dimensions [5]. In the graphite structure, carbon atoms are connected with strong covalent bonds of a type called sp^2 bonds. These bonds hold the sheets together, and there are also weaker Van der Waals bonds between the sheets. Because of these weak bonds, graphite is a soft material. This is different from diamond, which is very hard because it has only strong sp^3 covalent bonds throughout its structure.

Graphene has a plane sheet of carbon just one atom thick, having outstanding characteristics. It possesses an impressive set of attributes, including an exceptionally high thermal conductivity of 5,000 $Wm^{-1}K^{-1}$, an elevated electrical conductivity of 108 Sm^{-1}, and also remarkable transparency at 2.3%. These features have piqued the interest of both researchers and engineers. Yet, the exceptional qualities of Graphene do not end there. They also exhibit outstanding mechanical strength along with a breaking strength of 42 Nm^{-1} and a Young's-

modulus of 1.0 TPa, rendering it exceptionally robust and flexible. Moreover, graphene has a substantial aspect ratio and boasts a significant specific SA of $2.63\times106\ m^2\ kg^{-1}$, further contributing to its distinct attributes [5 - 10].

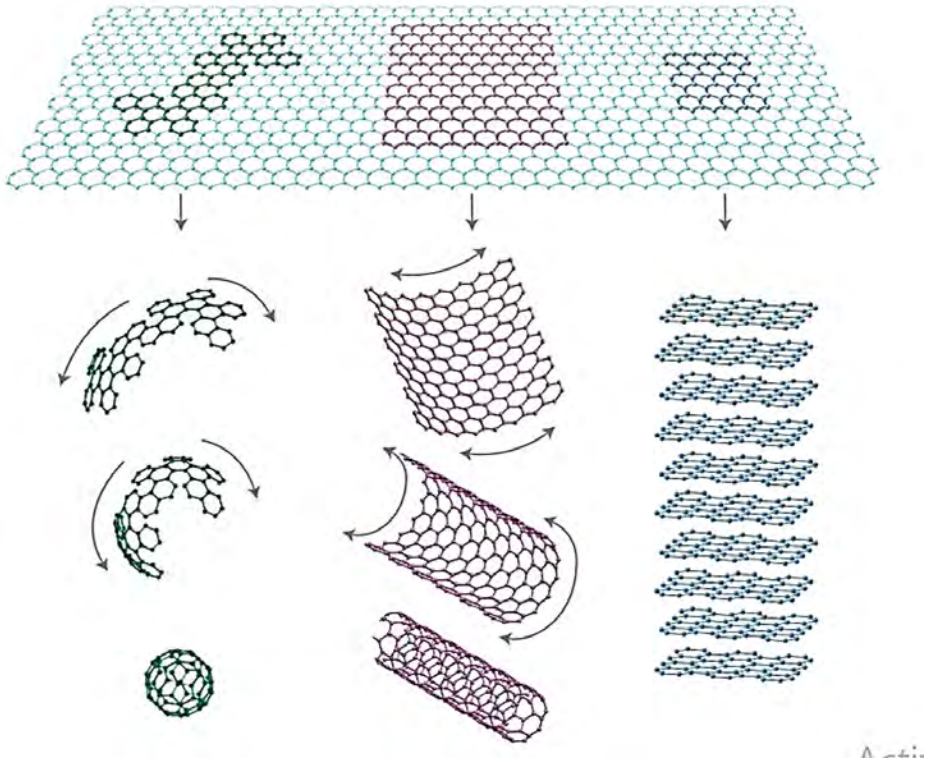

Fig. (1). Illustrates various morphologies within the carbon materials family, including fullerene (0D), nanotube (1D), graphite (3D), and the fundamental component, graphene (2D) [5].

Graphene stands out as a game-changing material for meeting the demand for clean and renewable energy on a worldwide scale thanks to its exceptional thermal and electrical conductivity, transparency, mechanical strength, flexibility, and significant surface area [11, 12].

As the research on Graphene advances, its potential for widespread utilization in energy-related applications is increasingly promising. Scientists and engineers across the globe are actively exploring the possibilities offered by this remarkable material, with its rapid ascent being well-documented in prominent scientific publications. In our quest to meet escalating global energy demands while addressing the challenges of pollution, global warming, and fossil fuel depletion, Graphene has emerged as a beacon of hope for a sustainable future.

CHAPTER 8

A Review of Crack Growth Analysis of Graphene Nanocomposites

Mamta Dahiya[1], Virat Khanna[2,*] and **Suneev Anil Bansal[3]**

[1] *Department of Mechanical Engineering, MAIT, Maharaja Agrasen University, Solan, Himachal Pradesh, India*

[2] *University Centre for Research & Development, Chandigarh University, Mohali, Punjab, India*

[3] *Department of Mechanical Engineering, Bharat Institute of Engineering and Technology, Mangalpally, Ibrahimpatnam, Hyderabad, Telangana, India*

Abstract: Graphene (Gr) has extraordinary properties such as excellent mechanical, electrical, and thermal strength. Adding Gr into the metal matrix enhances the overall properties of the nanocomposite (NC). The advantages and disadvantages of any kind of NC depend on various defects such as vacancy, holes, cracks, *etc.* and these defects depend on the type of application. This review article presents an extended finite element method (X-FEM) to model and analyze the mechanical properties of graphene nanocomposites (GNC). X-FEM is an excellent tool to analyze crack growth in graphene sheets (GS) and GNC. This FEM analysis is performed using different properties such as Young's modulus, Poisson's ratio, and mass density. It has been observed from the review that aligning and distributing GS randomly enhances the mechanical properties but if crack formation occurs in the NC or on the GS then properties start degrading.

Keywords: Crack growth, Graphene, Poisson's ratio, Simulation.

INTRODUCTION

Production of graphene (Gr) has enhanced exponentially in recent years due to its effective contribution in different applications for example automotive, aerospace, biomedical, and energy storage devices, *etc.* There have been extensive studies available that reveal greater enhancement in nanocomposites (NC) by adding Gr for example showcasing excellent mechanical, electrical, and thermal conductivity. The addition of graphene sheets (GS) into NC ranging from polymer to metal non-metals leads to significant improvement in the stiffness and strength of NC. Various computational studies such as Quantum Chemistry, finite element

* **Corresponding author Virat Khanna:** University Centre for Research & Development, Chandigarh University, Mohali, Punjab, India; E-mail: khanna.virat@gmail.com

Virat Khanna, Vishal Chaudhary, Anam Munawar, Reddicherla Umapathi and Kamaljit Singh (Eds.)

analysis (FEA), molecular dynamics (MD), and Monte Carlo (MC) methods, *etc.* have been conducted to develop GNC and find various properties exploring the potential of GNC [1, 2]. Zhang *et al.* have estimated the mechanical properties of Gr having defects using MD. They have concluded that the mechanical characteristic of Gr has been more sensitive to temperature compared to the increasing number of layers of Gr [3]. An accurate estimation of 3D structures is very important from a safety point of view. There are many components used in engineering, for example, automobile parts, aircraft components, and other structural parts that go under cyclic loading in their working period. This may be subject to failure due to crack growth of elliptical or semi-elliptical shape growth with repeated loading and then structures fail due to the continuous loading. Therefore, there is a great need to know the exact reason for failure or crack growth. The analysis of crack growth with the help of simulation is a great method and has been widely used in various failure analyses.

There are a number of studies available in the literature related to standard crack growth but in real structures, cracks carry an arbitrary shape. The analysis of irregular shape crack growth is difficult from a safety point of view. Therefore, analysis through simulation is the best way to analyse 3D irregular-shaped crack growth. Different engineering parts can be analysed accurately using fracture parameters *i.e.* stress intensity factor and growth of different shaped cracks in different directions can be acquired by maximum principal stress (mp_s). According to experimental studies, defect-free Gr exhibits Young's modulus of 1.1 TPa and is considered to be a sturdy material with an ultimate strength of 130 GPa [4].

In previous studies, the finite element method (FEM) has been considered the best method for the analysis of already present cracks and for growing cracks. The successful modelling and analysis need fine meshing approaching cracks and re-mesh when the crack starts growing. Therefore, there is an extended method that is used to estimate crack growth called the extended finite element method (X-FEM). In this method, irregularities for example cracks, inclusion, and holes have not been selected as a part of the FE mesh. One of the articles presented by researchers Sukumar *et al.* has explained X-FEM and the modelling and simulation of a regular-shaped crack.

Further, the main objective of this review is to highlight the factors controlling strength and damage in GNC with the computational method *i.e.*, X-FEM. Here, we are also showcasing the GNC interfacial effects and the role of their structural defects such as Gr clustering, different orientations, cracks, *etc.* in fractural properties. For different findings, the method X-FEM is discussed to evaluate different irregularities or discontinuities.

MODELLING

There are various theoretical and computational works that have already been performed on graphene nanocomposite GNC, for example, Awasthi *et al.* have worked on load transfer mechanisms in GNC using the molecular dynamics (MD) technique [5]. Cho *et al.* have used the Mori-Tanaka method to find elastic properties of GNC having a random dispersion of GS in the matrix [6].

To complete the objective of fracture analysis, first, we have to evaluate equivalent properties of GNC such as Young's modulus, Poisson's ratio, and fracture toughness. Then, simulation has to be done through X-FEM to perform crack growth analysis throughout the NC which especially considers edges and centre-cracked GNC.

For example, in the analysis of aluminium GNC, a cubical shape RVE of length 100 mm is constructed as aluminium matrix and a circular GS of 20 mm is reinforced in the Al matrix. GS are distributed uniformly in the RVE cube maintaining homogeneity. GS thickness is assumed to be 2mm. A 3D static analysis is performed on ABAQUS to examine elastic modulus and yield strength at different concentrations of Gr. A 3D linear tetrahedron element (C3D4) is used for AlGr NC [7]. For the arrangement, the mechanical properties of Al and Gr considered are shown in Table **1** and Fig. (**1**) shows the NC RVE model used in finite element analysis with GS and without GS.

Table 1. Mechanical properties of Al and Gr.

Material	E	ν	Reference
Gr	1.1 TPa	0.165	[8]
Al	0.7 TPa	0.34	[9]

EXTENDED FINITE ELEMENT METHOD

X-FEM is a numerical method to analyse crack development in nano-material with loading. X-FEM is based on dividing the unity method where rupture can be modelled independent of the FE mesh. X-FEM is already a popular computation method to solve differential equations and various models have been already proposed for crack growth in FEM. This method is suitable for simulating interface cracks but is not able to simulate the unknown crack path. For this purpose, the X-FEM method is used to calculate arbitrary discontinuity caused by cracks. This method has the ability to analyse crack growth in structural and un-structural mesh [10]. X-FEM is also known as a generalized finite element method or partition of unity (PoU) method. PoU is used to eliminate conformal

CHAPTER 9

Graphene-based Materials for Electrochemical Energy Storage Devices-EESDs; Opportunities and Future Perspective

Khizra Arif[1,*], Abdul Shakoor[2], Muhammad Awais[3], Marvi Dashi[4], Behram Khan Ajat Khel[5], Sami Ur Rehman[6], Khansa Masood[7], Farah Hussain[7], Waheed Alam[8] and **Muhammad Atif[9]**

[1] *Department of Material Science and Engineering, Institute of Space Technology, Islamabad, Pakistan*

[2] *Department of Physics, University of the Punjab, Lahore, Pakistan*

[3] *COMSATS University, Islamabad, Pakistan*

[4] *Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan*

[5] *Department of Chemistry, Abdul Wali Khan University Mardan, Mardan, Pakistan*

[6] *Department of Physics, Riphah International University, Islamabad, Pakistan*

[7] *Department of Physics, International Islamic University Islamabad, Islamabad, Pakistan*

[8] *School of Physics, Minhaj University, Lahore, Pakistan*

[9] *Institute of Metallurgy and Materials Engineering, University of the Punjab, Lahore, Pakistan*

Abstract: The material's exciting properties, which have substantially expanded the field of study, include its enormous surface area, outstanding electrical conductivity, extreme thinness, amazing electron kinesis, and cutting-edge mechanical control. These topographies are largely active for various energy-storage devices (EESDs) such as supercapacitors, hybrid cathode and anode materials, lithium-sulfur batteries, lithium-ion batteries, lithium-oxygen batteries, and sodium-ion batteries. The scalability, stability, and uniformity of nanomaterials made of carbon are essential for the development of graphene-based energy storage devices.

Keywords: Energy storage, Electrochemical energy storage devices, Graphene, Sustainable development.

[*] **Corresponding author Khizra Arif:** Department of Material Science and Engineering, Institute of Space Technology, Islamabad, Pakistan; E-mail: khizraarif777@gmail.com

Virat Khanna, Vishal Chaudhary, Anam Munawar, Reddicherla Umapathi and Kamaljit Singh (Eds.)

INTRODUCTION: GRAPHENE-BASED MATERIALS FOR ENERGY STORAGE

Lithium Sulphur battery is among the most cutting-edge and well-known energy storage technologies with a wide range of uses. Due to its exceptional qualities and peculiar two-dimensional structure made up of atoms that are one atom thick, graphene materials have gained much consideration in the production of lithium sulphur batteries. Li-Sulphur batteries offer the best prospects for meeting the escalating need for high-energy storage devices. With a specific capacity of roughly 1673 mAh g1, sulphur (S) cathode has the highest specific capacity among solid elements. Theoretical studies reveal that sulphur cathode has the capacity to deliver 2600 Wh-kg, or around five times the specific energy of the most well-known embedded compound electrodes ($LiCoO_2$ and $LiFePO_4$) [1 - 3].

In contrast, lithium sulphur batteries may generate an average voltage of about 2.2 V, less voltage of conventional ($LiCoO_2$-graphite) batteries *i.e* >3 V. However, the Li-S battery's enormous capacity can successfully counteract its low voltage profile. Because lithium sulphur batteries are made of toxic-free as well as environmentally friendly components. Sulphur is the 10th most common element in this universe, a byproduct of turning fossil fuels into useable energy sources like petrol. Due to its natural abundance and inexpensive cost, S is a preferred material for positive electrodes in contemporary lithium batteries [4]. Fig. (**1**) shows the schematic representation of a standard lithium sulphur battery.

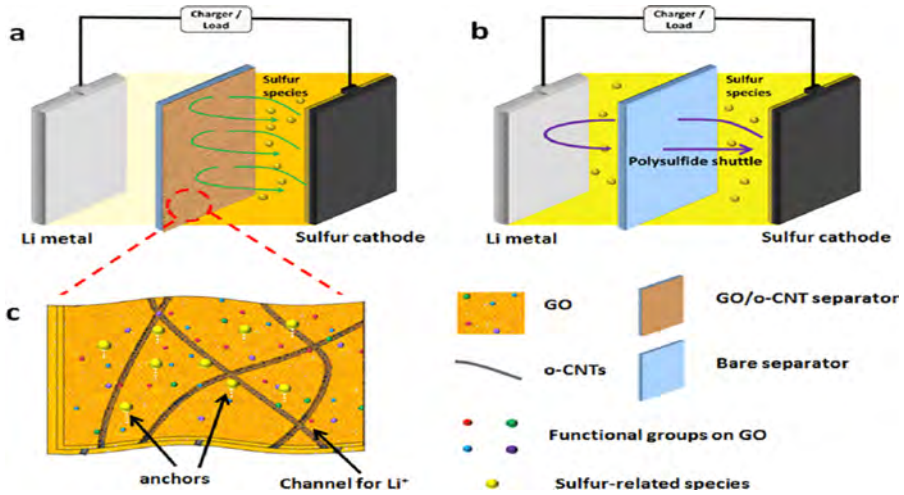

Fig. (1). (a). Schematic representation of a standard lithium sulphur battery; **(b)** a schematic diagram of a lithium sulphur battery along with Graphene sandwiched between plates. The diminished shuttle effect is represented by the lighter shade of yellow. RSC and Wiley-2014.

Lithium anode, a sulphur cathode as well as liquid/solid electrolyte separator typically make up a lithium sulphur battery. The following equation can be utilized to represent the basic electro-chemical reaction of lithium sulphur cells:

$$Li_2S = S+2Li.$$

In the -ve electrode, lithium is oxidised to lithium-ions, and in the +ve electrode, Sulphur is reduced to S_2 ions. In actuality, the intricate systems include multi-step reactions and are exceedingly complex. Elemental sulphur having ring-structured, S_8-phase is subsequently converted into long-chain polysulfide during the initial stage of the discharge process.

The polysulfide's chain lengths are then reduced, resulting in the formation of lithium sulphide (Li_2S). Consequently, depending upon the carbon content of sulphur electrodes as well as discharging rates, also the lithium sulphur battery having a discharge curve often contains two to three voltages linked towards reduction phases of Sulphur. In the late 1960s, lithium sulphur batteries were researched for many years, and a lot of development has been accomplished (Fig. **2**). However, before they can be used in actual applications, the following problems with these batteries must be resolved [5 - 8].

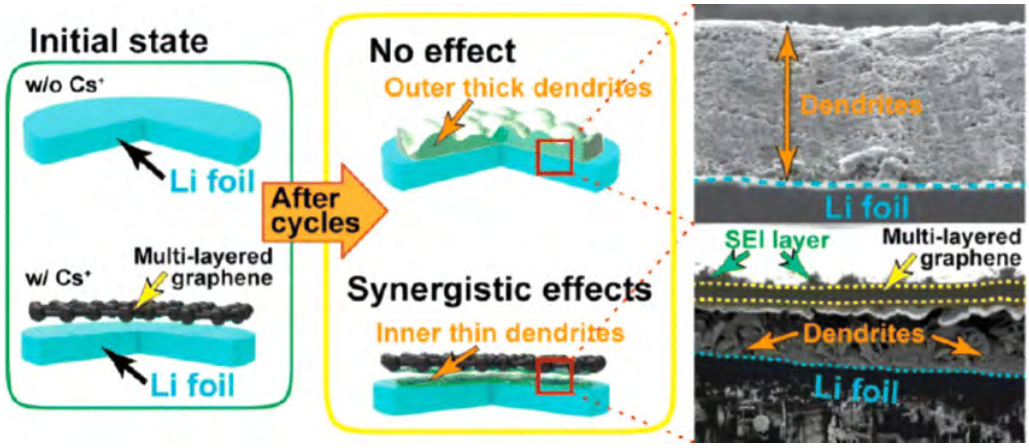

Fig. (2). (a) Different lithium dendritic development processes are dependent on multilayer Graphene and Cs ions. 2015 ACS. All rights reserved. Diagrams of a lithium-metal anode showing its many structural states during lithium deposition and dissolution are shown in (b) and (c): The graphene anode shows a uniform and stable lithium deposition with low resistance and relatively high efficiency. (b) Excluding the graphene framework, lithium dendrites emerge during lithium deposition. 2015 ACS Copyright.

The charging transports in cathodes are blocked by elemental sulphur and its final discharge outcomes, *i.e.*, Li_2S/Li_2S_2, which are electrically insulating materials

CHAPTER 10

Effect of Graphene on the Microstructure and Mechanical Properties of Metal Matrix Composites

Kamaljit Singh[1,*], Virat Khanna[2] and **Vishal Chaudhary[3]**

[1] *Department of Mechanical Engineering, Chandigarh Engineering College, Jhanjeri, Mohali, India*

[2] *University Centre for Research & Development, Chandigarh University, Mohali, Punjab, India*

[3] *Department of Physics, Bhagini Nivedita College, University of Delhi, Delhi, India*

Abstract: Metal Matrix Composites (MMCs), an advanced class of materials with exceptional mechanical properties and tailored functionality have emerged as a promising option for a wide range of applications. Graphene, a two-dimensional carbon allotrope with remarkable properties, has the potential to further enhance the structural integrity and mechanical performance of MMCs when integrated into them. Therefore, this article reviews the results obtained from a thorough examination of the microstructure and mechanical properties of metal-based composites, focusing on the impact of graphene reinforcement. The microstructure and mechanical characteristics of graphene-based MMCs are highly influenced by the amount of graphene present, the process used, and the presence of defects. In general, graphene addition has shown improvement in the mechanical strength, and hardness of MMCs due to refinement in grain size. MMC characterization techniques such as scanning electron microscopy, transmission electron microscopy, Raman spectrum and X-ray diffraction have been discussed to understand the graphene's dispersion, interfacial bonding with metal, and crystallographic changes in MMC. Based on the outcomes, it can be concluded that graphene-based MMCs have the potential to revolutionize a wide range of industries, from aerospace and automotive to electronics and energy storage.

Keywords: Graphene, Hardness, Microstructure, and applications, Tensile strength.

INTRODUCTION

Currently, metal matrix composites (MMCs) are highly sought-after materials from an industrial perspective. Constant development in the processing methods combined with the ability to add a wide range of reinforcing materials has allowed

[*] **Corresponding author Kamaljit Singh:** Department of Mechanical Engineering, Chandigarh Engineering College, Jhanjeri, Mohali, India; E-mail: kamaljit36@gmail.com

mass production of MMCs with ample application in different sectors [1 - 3]. MMCs offer a combination of properties that cannot coexist in pure metals [4].

MMCs consist of a metal or alloy matrix reinforced with ceramic, metallic, or organic compounds [5]. The integration of different reinforcing materials serves to enhance specific properties, including but not limited to strength, wear resistance, and electrical and thermal conductivity [6]. Aluminium (Al), Copper (Cu) and magnesium (Mg) are some of the prominent metals extensively employed in the manufacturing of metal matrix composites (MMCs), among other materials such as titanium (Ti), nickel (Ni), and iron (Fe) [7, 3]. As this material displays excellent properties like high specific strength, good wear and corrosion resistance, low density, and high specific stiffness, they are extensively utilised in the aerospace sector, automotive manufacturing, high-speed vehicle brake discs, and shipbuilding applications [8 - 12]. The strength of MMCs relies principally on the specific type of reinforcing materials employed [13]. By utilising the inherent qualities of its constituent elements, they are better able to modify the properties of the composites. Typically, ceramics such as Al_2O_3, SiC and WC are incorporated into the metal matrix as reinforcement to enhance the mechanical strength of the parent material [14]. However, their presence in the metal matrix adversely affects the ductility and conductivity of the composite [15 - 17].

Over the past few years, a novel class of strengthening additives known as carbonaceous nanomaterials, including carbon nanotubes (CNTs), fullerenes, and graphene, has emerged [18]. When these reinforcements are integrated into pristine metal matrices, they not only enhance the physical and mechanical properties of the parent metal but also introduce a wide range of functional properties, such as tribological characteristics and, electrical and thermal conductivities [18 - 20]. These nano-sized reinforcement materials have exhibited a significant advancement in the properties of metal matrices when compared to conventionally employed macro-sized reinforcements [21].

Graphene among various nanomaterials, stands out due to its exceptional properties, leading to extensive research conducted over the past decade for the development of graphene graphene-reinforced MMCs [22]. Graphene, a two-dimensional carbon allotrope, has gained significant attention in recent years due to its exceptional mechanical, electrical, and thermal properties [23]. When incorporated into MMCs, graphene can enhance several important properties, leading to improved performance in various applications [24].

During the initial phase of the investigation, single-layer graphene (SLG) demonstrates remarkable properties across various domains. It showcases exceptional electron mobility, reaching a value of 200000 cm^2 V^{-1} s^{-1}.

Additionally, SLG demonstrates exceptional thermal conductivity, measuring 3000 W·m/K, and possesses remarkable mechanical strength, boasting Young's modulus of 1 TPa and tensile strength of 130 GPa. Alongside these impressive characteristics, SLG showcases high chemical stability and a remarkably high theoretical specific surface area of approximately 2600 m^2/g [16, 23, 25].

By adding graphene to a metal matrix, such as aluminium, copper, or titanium, the resulting MMC can exhibit enhanced mechanical strength. For example, the incorporation of graphene nanoplatelets (GNPs) in the aluminium alloy (AA1100) has shown a significant improvement in both the yield strength and ultimate tensile strength. The maximum reported values for yield strength (YS) and ultimate tensile strength (UTS) are 155.67 MPa and 170.28 MPa, respectively, for the AA1100/1.2% GNP metal matrix composite (MMC). These values represent an increase of 40% and 30%, respectively, compared to the unreinforced aluminium alloy. This indicates that the addition of 1.2% GNPs has led to a substantial enhancement in the mechanical properties of the composite [26]. This enhancement in strength is majorly due to the exceptional properties of graphene that exist within the MMCs as a reinforcement.

SYNTHESIS AND CHARACTERIZATION OF GRAPHENE

Different Methods used for the Synthesis of Graphene

Currently, the methods for synthesizing graphene can be classified into top-down and bottom-up approaches as shown in Fig. (**1**) [27]. The top-down approach encompasses the structural disintegration of a precursor material like graphite, which is subsequently followed by the separation of its layers through techniques, namely mechanical exfoliation, oxidation–reduction of GO, liquid phase exfoliation and arc discharge to attain individual graphene sheets. In the bottom-up method, a carbon source is utilized for the synthesis of graphene on a substrate using chemical vapor deposition, epitaxial growth, and total organic synthesis techniques [28].

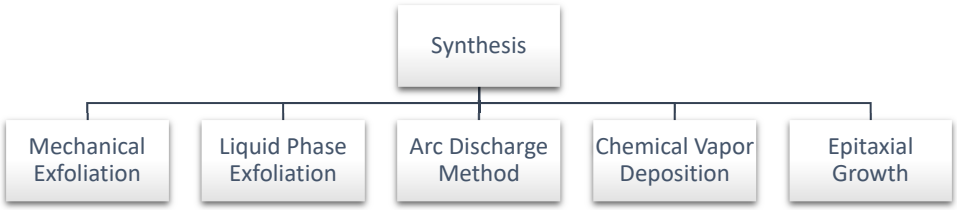

Fig. (1). Illustrates common approaches to synthesize graphene [29, 30].

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Virat Khanna

Virat Khanna works as an Associate Professor at the UCRD, Chandigarh University, Punjab, India. He has more than 14 years of experience in academics and research. He has authored more than 30 national and international publications in SCI, Scopus, and Web of Science indexed journals. He is the editor of several books and conference proceedings with various international publishers like Springer, Elsevier, CRC Press, IGI Global and Bentham Science Books. He has delivered several invited seminars and keynote talks on international platforms and has been awarded with best research paper awards. He is also the academic editor of the "Journal of Nanotechnology", Wiley and "Advanced Materials Science and Engineering, Wiley and is also the Book Series Editor entitled 'Recent Advances in Materials for Nanotechnology of CRC Press, Taylor & Francis-Publisher. He is also the guest editor of various special issues with various international journal publishers like Springer, De Gruyter etc.. He is also the reviewer board member of several international journals.

Vishal Chaudhary

Vishal Chaudhary has been an assistant professor of physics at the University of Delhi since 2015. His research interests include nanomaterials, green nanotechnology, sensors, environmental remediation, one health and non-invasive diagnosis. He has published more than 90 research publications, 9 book chapters, authored 4 books and edited 2 books. He has been listed in top 2% scientists in the world and awarded with many prestigious awards. He is founder of Happy Mentals Club, which is dedicated to spread awareness about mental health and research for different neuro-/mental health aspects

Anam Munawar

Anam Munawar is an assistant professor at the University of Health Sciences, Lahore. She completed her Ph.D. in 2020, from Pakistan Institute of Engineering and Applied Sciences (PIEAS), Islamabad. Her area of interest is biosensors and biomimetic sensors technology; system miniaturization and applications (bio)chemical molecular recognition layers for separation and sensing applications, artificial receptor materials via molecular imprinting technique, development of sensitive and selective coatings for mass-sensitive, microelectrode, and electrochemical devices; substantiating developed materials and surfaces by using various characterizing techniques, establishing mechanistic studies for their potential applications in real environment.

Reddicherla Umapathi

Reddicherla Umapathi obtained Ph.D. in chemistry in 2017 from University of Delhi, Delhi, India. He worked as postdoctoral research fellow at Chungnam National University, South Korea and National Taiwan University, Taiwan. Since 2019, he is working as a principal researcher at the NanoBio High-Tech Materials Research Center, Inha University, South Korea under the support of Brain Pool Fellowship, a prestigious outstanding invited scientist grant from National Research Foundation of Korea. He is an associate fellow of Andhra Pradesh Akademi of Sciences, Andhra Pradesh, India. His research focuses on electrochemical sensors, gas sensors, and energy harvesting.

Kamaljit Singh

Kamaljit Singh did Ph.D. in mechanical engineering from Maharaja Agrasen University. He is currently working as assistant professor at Chandigarh Engineering College. His passion for mechanical engineering is reflected in his research interests in nanomaterials, composites, non-conventional machining methods, and additive manufacturing. He has to his credit a number of scientific papers and book chapters worldwide.