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The Impact of COVID-19 on the Global Graphene Industry

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Abstract

Graphene materials with superior electrical and mechanical properties are driving innovations and development of technologies in areas of medicine, electronics and energy. The rising demand for new materials that are stronger, flexible and more efficient for various applications has accelerated the growth of graphene industry. However, the unexpected outbreak of COVID-19 pandemic has affected the graphene industry in various aspects. Extensive studies have been carried out in this work to describe the impact associated with the outbreak, particularly on biomedical and electronics applications. This study also summarized several challenges to be addressed prior to commercializing the use of graphene in the industry and general potential measures to be taken for crisis management during COVID-19 are included.

Keywords: Graphene; COVID-19; biomedical; Electronics; Applications

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Introduction

The outbreak of coronavirus disease 2019 (COVID-19) pandemic across the globe has disrupted the global political, social, economic and financial structures. The national outputs of developed and emerging economies are expected to contract by 6% in 2020 with gross domestic product (GDP) of -4.7% to -8.1% depending on the region. Various sectors such as tourism, consumer electronics, financial markets and transportation are severely impacted due to the uncertainty and unpredictable spread of COVID-19. Amongst many sectors that are recovering, graphene industry, a sub-category of nanotechnology and Nano engineering which is under sturdy growth since 2014 is experiencing an accelerated growth during the pandemic [1,2]. The graphene industry involves materials that consist of single or few layers of carbon network bonded in hexagonal honeycomb lattice and are allotropes of carbon having sp^2 hybridized carbon atoms with a molecular bond length of 0.142 nm. Graphene exhibits unique properties such as lightweight, flexible, high electron mobility and excellent electrode-channel contact that are suitable for a wide range of applications in biomedical, pharmaceutical, electronics, aerospace, automotive and energy industries [3] **(Figure 1)** [4].

Literature Review

The global graphene market valued USD 32 million in 2016 and is

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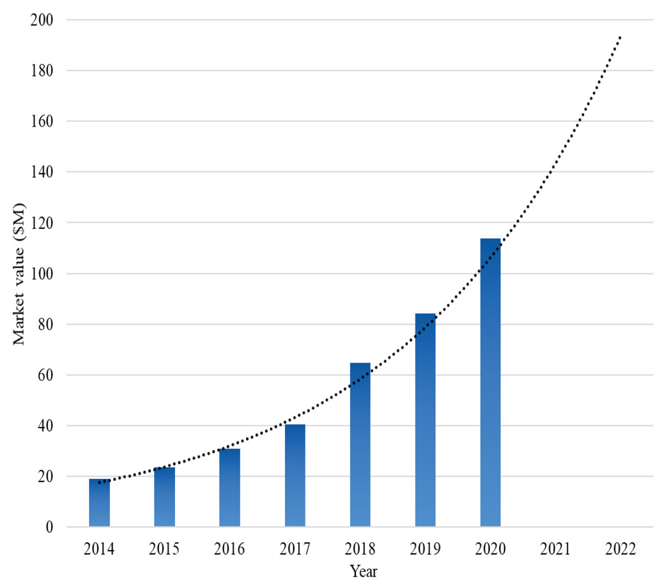

Figure 1 Global graphene market from 2014 to 2020 plotted with the expected exponential growth up to year 2022 [4,5].

expected to reach USD 193.68 million in year 2022 as illustrated with Asia Pacific as the largest region for consumption and application [5]. The graphene market in China is increasing at an exponential rate since 2014 as medical, energy, defense, electrical and electronics sectors develop in line with the national goals set by the Chinese government [6]. Numerous studies have been conducted to commercialize the use of graphene materials, in particular, the electronics, semiconductors and aerospace sector comprised of >50% use of graphene materials in 2019. The global graphene market is anticipating a compound annual growth rate of 70%, both in volume and revenue through 2020 to 2025 due to the increasingly strong demand for graphene materials in electronics and healthcare sectors for medical sensors and drug carriers during the COVID-19 pandemic **(Figure 2)** [7-9].

Impact on biomedical applications

The biomedical industry is growing at a faster pace due to the outbreak of COVID-19. Much effort and innovations have been initiated in extending existing applications to respond to this global outbreak. Graphene, with antimicrobial and antiviral efficacy, has triggered the interest of scientific community in exploring its applications in the prevention, detection and treatment of COVID-19.

Leading companies and research institutes in graphene industry have developed prophylactic or protective face masks by utilizing graphene-enhanced polymers such as non-woven textiles modified with graphene materials [10]. The sharp edges of graphene are believed to damage the cell membranes whilst the hydrophobic property of graphene induces dehydration and eventually leading to cell death. Research reports that the produced graphene masks show anti-bacterial efficiency of 80%; and the photo thermal effect of graphene further enhances the anti-bacterial effect up to 99.998% under sunlight exposure for 10 minutes [11]. Research has also been carried out to incorporate graphene in air purification products to mitigate the threat of virus infection [12].

The early diagnosis of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) that causes COVID-19 is mandatory to prevent severe outbreak of the disease. Exiting detection strategies include immunological assays, detection based on amplification techniques and bio sensing. Immunological assays involve complex production routes for recombinant proteins and antibodies whilst amplification approaches require skilled operators and costly instruments [13]. As the current pandemic demands rapid, accurate and reliable detection strategies to mitigate and break the transmission chain of COVID-19, biosensors appeared to be a potential technique for facile detection of the virus. Biosensors generally consist of a bio receptor that targets analytes such as antibodies, enzymes and DNA; and a physiochemical transducer that receives, converts and amplifies signals from biomolecule-analyte interaction to measurable information [14].

Graphene materials with exceptional high surface to mass ratio and can achieve single-molecule detection have been widely applied for the detection of viral pathogens, viruses and vitamins with high specificity [15]. Biosensors fabricated from graphene composites such as graphene-nafion composite film, gold nanoparticles-decorated reduced graphene oxide (rGO) Nano composite, molybdenum disulfide and rGO decorated with gold nanoparticles Nano composites and silver nanoparticle-graphene-chitosan Nano composite demonstrated the detection of various pathogenic viruses with a detection limit of 1.6 pg/mL to 3.8 ng/mL [16-19]. These biosensors allow highly sensitive and fast detection of biomolecules [20]. The strong interaction between reaction sites on the surface of graphene materials with

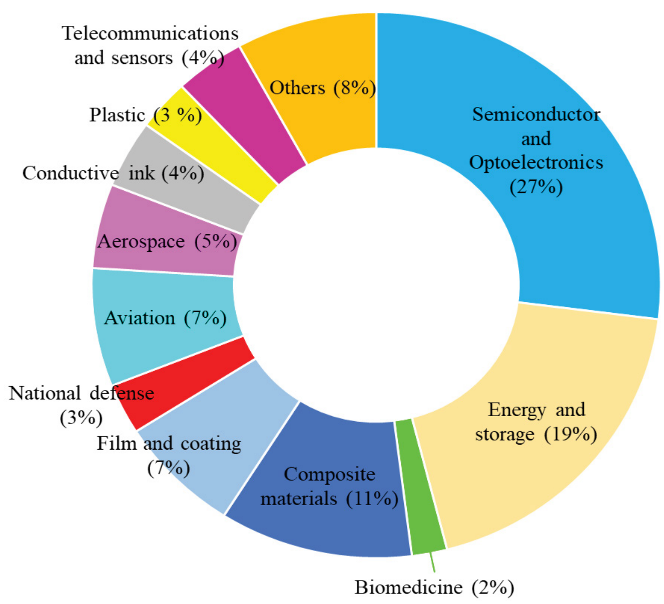

Figure 2 Global application of graphene in different sectors [9].

protein, enzymes and nucleic acid demonstrated its suitability as sensors for SARS-CoV-2 detection. The rapid detection of SARS-CoV-2 spike proteins for large population screening is realized via antibody-conjugated graphene oxide (GO) sheets with unique electric field effects and electrochemical properties for signal amplification [21]. A field-effect transistor biosensor is developed by using 1-pyrenebutanoic acid succinimidyl ester as a probe linker for the detection of SARS-CoV-2. This biosensor detects the virus both in transport medium or clinical sample with a detection limit of 1 fg/mL [22].

Apart from early protection and detection, researchers have also developed graphene-based coatings for clinical settings or high-traffic areas that are effective in destroying SARS-CoV-2 membranes upon contact. Apart from physical damage to the membrane caused by the sharp edges on graphene upon impact, the graphene coating is expected to exert additional oxidative stress on the viral membrane to terminate membrane growth, eventually leading to cell death [23]. The unique hydrophobic property of this graphene coating ensures lasting protection on a surface for up to 60 days.

Polyglycerol sulfated graphene functionalized with fatty amine chains demonstrated successful inactivation of a coronavirus herpes simplex virus type 1 via the disruption of lipid bilayer. The hydrophobic interactions between graphene-amine composite chains and virus lipid bilayer exhibit antiviral activity against the virus [24]. Graphene materials mainly interact with viruses through hydrogen bonding, electrostatic interactions and redox reaction by binding to the aromatic planes and destroying the membrane [25]. Early study on GO demonstrated that GO has preferential binding on the DNA enzymes of viruses and thus is a potential candidate to be used in drug delivery systems and antivirus therapies [26]. Hypericin, a possible drug for COVID-19 treatment is combined with GO for virus inhibition. GO-silver Nano composites are also used to enhance the production of interferon-α and IFN-stimulating genes for natural antiviral defenses against COVID-19 [27,28].

Impact on information transfer and electronic applications

Graphene materials with unique mechanical and electronic properties such as high capacitance, good thermal conductivity and field emission, have been studied extensively to design energy storage materials, photovoltaics, nanoelectronics and optoelectronics for various applications [29,30]. The production facilities of the global electronics industry are experiencing negative impacts due to logistic slowdown and limited availability of workforce. Countries that are leading the electronic industry such as China, United States (U.S.), Germany and India are affected by the pandemic. As the largest manufacturer and exporter of electronic parts, the disruption of production line in China has forced other electronic manufactures based in the U.S. or Europe to hold the final assembling of finished goods. American Chamber of Commerce in Shanghai reports two-third of U.S. businesses operating in China is affected by the gap between demand and supply in the industry [31]. Despite consumer electronics are predicted to experience the most severe impact, other electronic products, particularly medical, tracking or remote monitoring devices are developing rapidly and are expected to surge during the pandemic. The demand for graphene materials in industrial or personal electronics supply chain might suffer the financial impact. However, the consequences are counterbalanced by the increasing demand for raw materials in the production of communication equipment, imagers and sensors for activity monitoring as well as biomedical applications throughout the pandemic.

Challenges, crisis management and future prospect

The global graphene industry is developing at a significant rate since its discovery. However, much effort and research are still needed to establish mature handling, processing, production and scale-up route mapping of graphene materials. It is acknowledged that the treatment and vaccination are urgent and necessary to combat COVID-19, but the implementation and attempt for commercial success in graphene during the pandemic should be carefully considered to ensure effective results. Typical challenges such as graphene instability or aggregation need to be addressed prior to its usage in drug delivery or vaccination. In addition, *in vivo* tests on dosage, surface chemistry and exposure route of the drug-graphene composite are necessary for full commercialization.

The graphene industry is expected to actively engage in the development of various tools and applications against COVID-19. However, corporate leaders should anticipate risks and consider opportunities as the market is responding and recovering from the coronavirus crisis. Corporations should avoid supply chain bottlenecks by reassessing the life cycle and identifying potential factors that will impact the operation, particularly those that are dependent on geographical locations. Consider risk factors and relevant impacts on commodity prices, supply chains and business continuity to ensure minimum disruption in the financial system.

Natural graphite is the common starting material for graphene synthesis. However, the over-exploitation of natural resources has raised global concerns and researchers are exploring biomass as an alternative to reduce the dependency on natural resources [32-34]. Biomass is referred to organic substances derived from living organisms that store solar energy in the form of chemical energy and studies showed the processing of biomass reduces the emission of carbon dioxide (CO_2) into the atmosphere due to its carbon neutrality [35-37]. Biomass feed stocks such as urea,, petals and food waste have demonstrated the successful fabrication of graphene materials; biomass extracts such as aloe vera and pine bark have also shown antioxidant properties [38-40]. Thus, biomass exhibit great potential in establishing a more sustainable approach for graphene synthesis for various applications, particularly during the pandemic.

Discussion and Conclusion

Extensive studies on nanomaterials have been carried out in the past decades to establish feasible production of graphene on an industrial scale for various applications. Graphene drives the development of technologies in automotive, electronics, energy and biomedical fields due to its unique properties as well as large potential and profitability in the market. The development of graphene technology and applications accelerated drastically during COVID-19 owing to its excellent conductivity, flexibility, antibacterial and antivirus efficacy. Graphene-based protective equipment, bio-sensors, drug delivery and treatment systems are developed to combat against COVID-19. In converse to biomedical and healthcare sectors, electronic and energy fields are experiencing a negative impact from COVID-19 due to logistic slowdown, decrease in demand and limited accessibility to raw materials for manufacturing. Nonetheless, with increasing demand and product use of graphene-based materials, the pandemic in general appeared to be boosting the graphene market growth in the coming years. However, limitations such as instability and dispersibility of graphene materials need to be addressed prior to full commercialization of graphene materials in the future.

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