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Graphene-based Materials for Fighting Coronavirus Disease 2019: Challenges and Opportunities

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Abstract

The coronavirus disease 2019 (COVID-19) caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is considered as serious global threat of this time and greatest challenge for recent days. Several approaches have been carried out in this direction to fight against COVID-19. Among these, nanotechnology is one of the promising approach to face these challenges in the current situation. Recently, graphene-based nanomaterials have been explored for COVID-19 due to its unique physicochemical properties. This mini review provides a recent progress in graphene-based nanomaterials and its applications for diagnosis, detection, decontamination, and protection against COVID-19. Further, main challenges and perspective for fundamental design and development of technologies based on graphene-based materials are discussed and suitable directions to improve these technologies are suggested. This article will provide timely knowledge and future direction about this wonder materials in various biological applications.

Keywords: COVID-19, Decontamination, Detection, Graphene, Protection

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1 Introduction

The coronavirus-19 is an infection was first reported from Wuhan city in China, caused by novel SARS-CoV-2 [1–3]. The disease affected different people in different ways and most of them were facing dry cough, fever, sore throat, headache, tiredness, etc. [4–6]. This kind of virus is spread from person to person or place to place via respiratory droplets resulting from sneezing, coughing, and physical touch. These respiratory drops have different sizes and most of them are sub-5 µm in size. The droplets, which have a size larger than 5 µm do not travel long distance and settle within 1–2 m because of gravitational force. However, the droplets with smaller size and light weight remain floating in air for long time, hence, they are increasing the spreading level of virus. Therefore, surgical masks provide a physical barrier that prevents exposure to respiratory droplet. COVID-19 has done political, environmental, and economical damages to societies worldwide. In this regard, both developing and developed nations are continuously working

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out to find a suitable solution for this pandemic. Among them, most of the work is done in detecting and curing COVID-19 and manufacturing different testing and diagnosis kits, development of vaccine, antiviral drugs, and other medical facilities [7–10]. On the other side, research is also going on the physical protection from COVID-19 by using various masks and respirators. In addition, the disinfecting and decontamination of human and public places such as hospitals, airports, offices, parks, shopping centers, etc. from COVID-19 is also important and several types of sanitization system and solution are developed and used.

Nanotechnology is one of the promising approach to face these challenges [11–14], and several types of nanomaterials have been introduced for diagnosis, decontaminations, detection, and protection against these pathogens since one year [13–18]. Recently, two-dimensional (2D) materials especially graphene-derived materials such as nanoporous-graphene-, graphene-oxide(GO)-, reduced GO(r-GO)-based technology has got significant interest in ionic sieving, molecular separation, desalination, gas-phase separation, dialysis, hemofiltration, nano-and ultra-filtration, water sterilization, sensors, protein separation, viral clearance, and other biomedical applications [19–37]. Graphene is a distinct atomic-thick layer of carbon atoms that is arranged in regular hexagonal-lattice. While GO is a functional derivative of graphene along with plenty of oxygen groups that containing functional clusters and that shows hydrophilic properties [37–39]. On the side, r-GO is a form of GO with less functional oxygen content and also hydrophilicity nature. Interestingly, graphene-based materials show both antimicrobial and antiviral efficiency [40–43]. The antibacterial properties of graphene material, and its derivatives are usually due to their electronic movement to virus or other germs. This type of electronic migration affects the lipid membrane, decrease metabolism, produce reactive species, in results the loss of glutathione and finally loss their lives. Several studies suggested that GO has the highest negative charge among all graphene derivatives and has high affinity for positively charged virus. Therefore, the lipid bi-layer of feline coronavirus adsorbed on surface of the GO, through hydrogen bonding as well as the electrostatic interaction. Subsequently, the binding of GO destroyed that viral membrane and confirmed the GO efficiency against viruses. Furthermore, surface of graphene can be changed to cross-linked with negatively charged antivirals like a drug, heparin, heparin-sulphate etc., which increase the affinity for positively charged virus. Similarly, GO can be also changed with respect sulphate derivatives effectively separate herpesvirus-strains, orthopoxviral, and swine-fever. This short review is focused on the important discussion of graphene nanomaterials for detection, diagnosis, decontamination, protection against COVID-19 and other pathogens (Fig. 1). The prospects and furthermore improvement of the graphene-based nanomaterials are detailed.

2 Role of Graphene-based Materials against COVID-19

2.1 Detection and Diagnosis of Coronavirus-19

The rapid spreading of the coronavirus-19 pandemic has generated several problems to human and no treatment has been developed for COVID-19 except some traditionally used

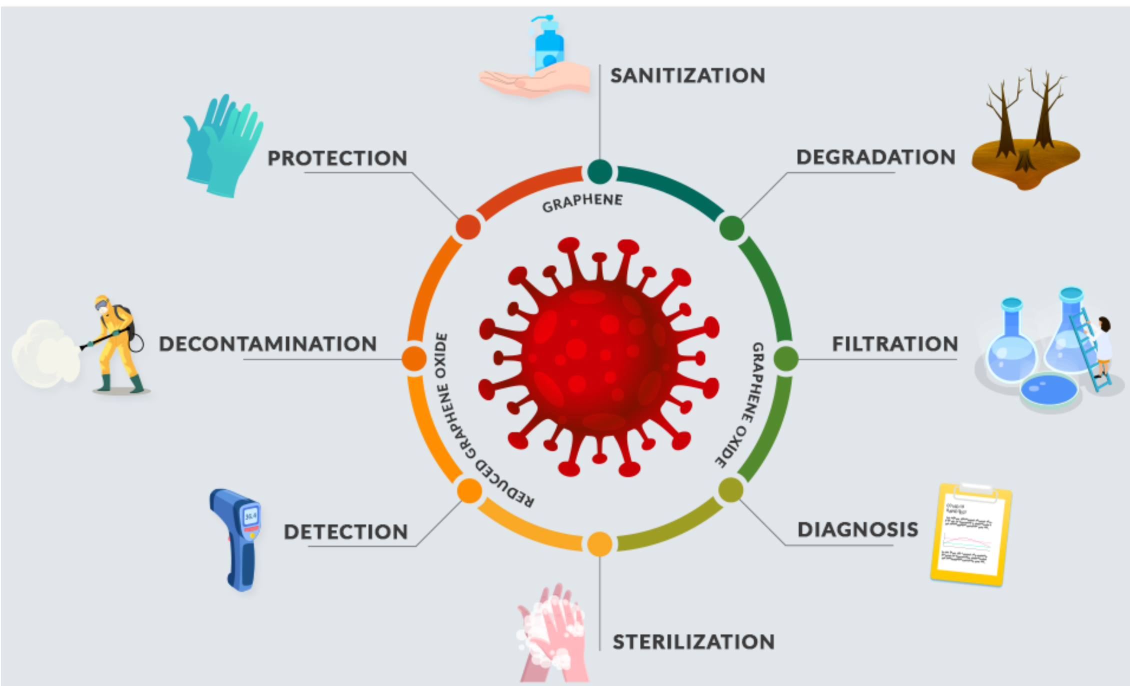

Figure 1. Graphene-based nanomaterial and their application against COVID-19.

medication to improve the immune system [44]. Beside this, there is also lack of detection and diagnosis system for COVID-19. Therefore, fast, accurate, sensitive and easy to use methods for testing are urgently required to overcome this issue before treatment. Currently, the most common test methods are RT-PCR kits, isothermal implications tests, serological tests, etc. are being widely used to diagnose the COVID-19 patient worldwide [45–48]. Among these methods, the nucleic-acid-based testing for respiratory specimens is the reference as a gold and standardized process for the diagnosis the patient of COVID-19 infected patients till now. Nevertheless, such kind of testing method are time consuming and the testing process requires a long procedure and suppose (a) extraction of viral RNA, (b) addition to a master mix containing nuclease-free water, reverse primers, a fluorophore-quencher probe, and a reaction mix, (c) loading of extracted RNA/master mix into PCR thermocycler and load, and (d) several cycles at settled temperature. RT-PCR uses respiratory samples to genetically detect COVID-19. In addition, the RT-PCR has several issues including very expensive laboratory analysis, and the technical expertise in carrying out the text and tested results. While serologic immunoassays and point-of-care technologies are also facing the same problems. The analytical process that is to evaluate the infection and immunity of SARS-CoV-2 and COVID-19 by antibody detection are crucial for epidemiological experiments, even though awareness, certainty, and testing laboratory are currently available everywhere in the market and that are not clear. Therefore, new strategies should be developed and deployed to improve testing capacity of SARS-CoV-2 with the help of chemistry, molecular science, and nanobiotechnology to protect and prevent human body from its environmental exposure. In this regard, the nanomaterial technology is playing a vital role for rapid diagnosis, monitoring, and design of the effective medicinal activities for COVID-19 due to their morphological similarities with SARS-CoV-2 [49–52]. In addition, nanoparticles are powerful tool to intercept a wide range of pathogens and viruses due to the possibility of surface modification and functionalization, providing high degree of specificity.

Recently, graphene-based nanomaterials are widely investigated for several bio-medical applications such as blood biomarkers, carriers for therapeutics, drug delivery, development of point-of-care diagnosis, vaccine, separation of bacteria from water and detection of virus such as Ebola, hepatitis C virus, H9N2 avian influenza, etc. [16, 33, 53–57]. Graphene-based detectors and sensors have attended significant interest during COVID-19 outbreak that can rapid detect the SARS-CoV-2 viral strain. Such sensors have great potential to replace RT-PCR kit, due to rapid detection within few minutes and high sensitivity. Beside bio-medical areas, such devices can be installed at point of entries such as airport, railway stations, bus stands, borders area, etc. and extended to other COVID-19 viruses. Recently, Kim et al. [54], fabricated a field-effect transistor(FET)-based device using graphene as coating materials, which has the ability to identify SARS-CoV-2 virus in clinical samples (Fig. 2a). This device was fabricated and designed with the graphene-coating sheets of the FET transistor with a specific antibody against the SARS-CoV-2 spike-protein (Fig. 2). Furthermore, the characteristics and performance of the device is evaluated against antigen-protein, cultured-virus, and nasopharyngeal swab-specimens from COVID-19-infected patients. As a fabricated device showed exciting results and detect SARS-CoV-2 spike-protein in phosphate buffered up to the 1 fg mL^{-1} and 100 fg mL^{-1} in clinical samples in one minute (Figs. 2d and e). In addition, graphene-based FET devices have also the capacity to identify (SARS-CoV-2) in cultured form up to ~1.6×10^{1} pfu mL^{-1}, and 2.42×10^{2} pfu mL^{-1} in clinical samples (Figs. 2b and c). This improved technology based on graphene coating has lot of benefits such as no sample preparation required, rapid response, more sensitive and could be used in line with many nasal swab tests over traditional methods. This in addition, this FET biosensor device has also capacity to differentiate between SARS-CoV-2 and other members of the coronavirus family. From these studies, it can be concluded that most of work has been carried out with graphene for finding the virus in body and diagnosing the patients. Furthermore, 2D materials such as MXene, TMDCs, MOFs, h-BN also show good antibacterial properties [58–68]. Therefore, future research should be carried out in this direction for better detection of pathogens including COVID-19. The graphene-based materials should be modified using these 2D materials to achieve good antibacterial and antiviral properties.

2.2 Physical Protection from COVID-19

Beside these measurements, physical protection from the virus and other pathogens is very important, and by the spreading of COVID-19 mainly the respiratory system and other vital organs are affected. The use of personal protection equipment (PPE) has increased all over the world to control this pandemic. Due to this, the world is currently facing shortage of PPE such as masks, face shields, respirator, etc. Recently, surgical masks, and respirators N95 can provide different levels of protection and have been widely used by patients, medical staff, and even public in highly risk areas [69]. As for surgical face masks, which are fabricated to resist the direct entry of fluid into the wearer's nose and mouth from a splash, cough, sneeze. They are not designed to resist aerosolized pathogen such as COVID-19 due to larger pore size. In addition, the surface of these face masks is hydrophobic in nature and water droplets remain on them, which might be contain dangerous viruses. Further, these masks cannot be sterilized because of low melting point (<130°C) and cannot be reused [70]. Among them, the N95 respirator is considered as most effective against virus (COVID-19), and commonly used by physicians and surgeons. The N95 certification showed that under standard conditions of this mask, that is protect the 95 % of the total bacteria in a salt's aerosol with average diameter size of 300 nm are resist by material. Though, this process is costly, the limited supply, and the filtration efficiency of mask is decreased up to 85 % for particles with size less than 300 nm [6, 71]. Therefore, N95 do not give required protection against SARS-CoV-2 virus, because it belongs to beta-coronavirus family with size in range of 65–125 nm [72]. Therefore, there is serious need to develop more efficient filtration mask and high-quality PPE for medical staff [70].

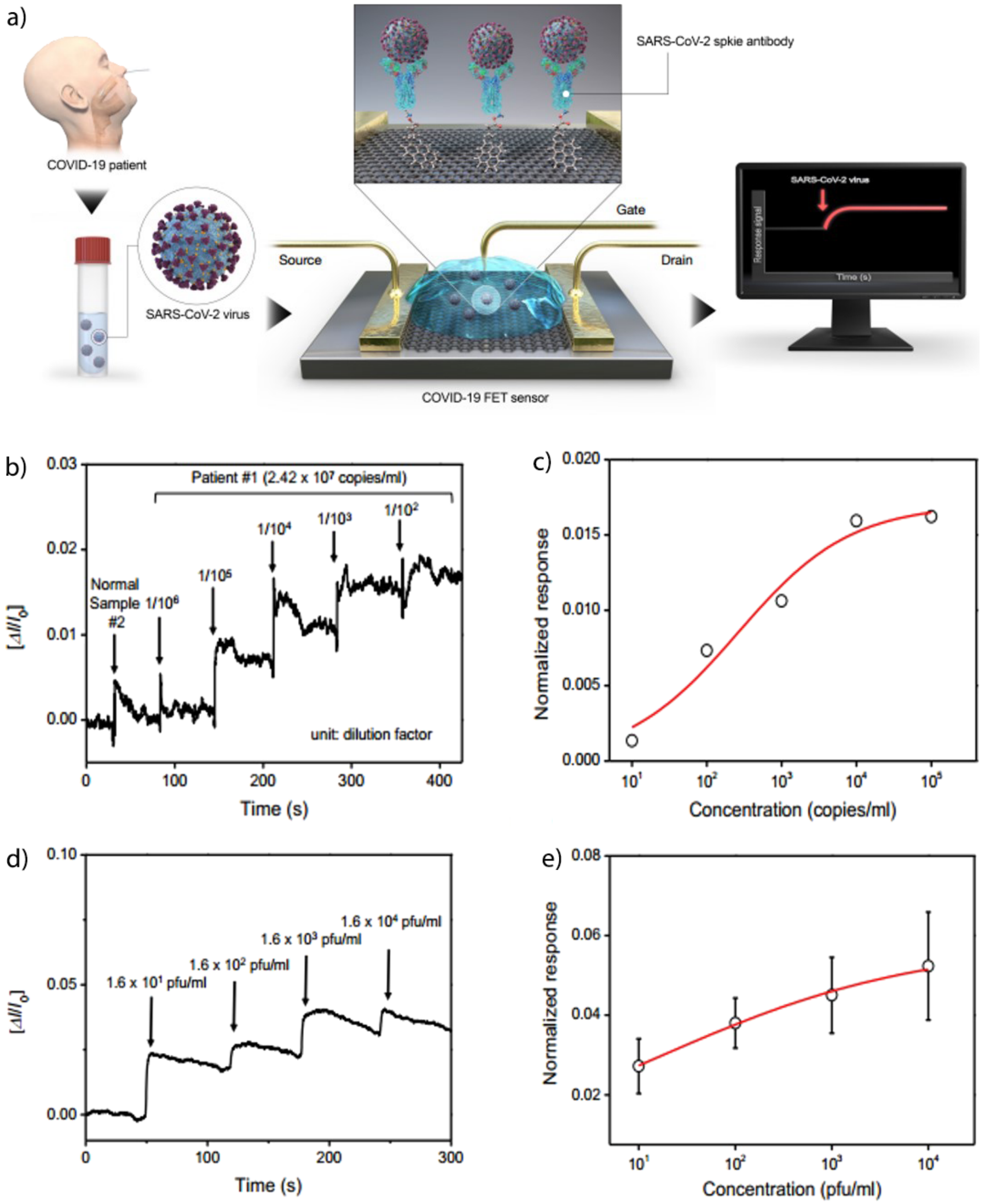

Figure 2. (a) Graphene-based FET sensor fabrication procedure for COVID-19. (b–e) Real time response of graphene-based FET device for SARS-CoV-2 in clinical sample (b, c), and cultured virus (d, e), Reprinted with permission from Ref. [54], Copyright © 2020, American Chemical Society.

Very recently, considering the antimicrobial, antistatic, and electrically conductive properties of graphene nanomaterials, various graphene-based face masks and membrane filters have been developed to face COVID-19 emergency. Such mask and filters have potential for self-cleaning and self-sterilization. In this regard, Li et al. [73] developed a graphene-based mask with advance superhydrophobic and photothermal properties that can be recycled and reused (Figs. 3a–c). Authors have deposited laser-induced graphene (LIG) onto the commercial surgical mask with help of dual laser induced forward transfer process to improve its superhydrophobic and photothermal properties (Fig. 3a). Furthermore, graphene-based coating also help to improve the self-cleaning capability of mask with a static contact angle of over 140° that is accomplished in (Fig. 3c). In addition, the surface temperature of the mask can be swiftly elevating to over 80 °C under the solar illumination, that is effectively sterilizing the virus. (Fig. 3). Additionally, several companies such as Bonbouton have developed reusable graphene masks that effectively block virus-containing microdroplets with its powerful graphene-infused filter [74]. ZEN Graphene Solution Ltd. and Graphene Composite Ltd. (GC) have developed a graphene-based composite ink for face masks and other PPE to fight COVID-19 [75]. They have synthesized silver nanoparticle-functionalized GO ink that effectively kills COVID-19 and influenza A and B viruses. Furthermore, Planar TECH & IDEATI's 2AM have also fabricated a cotton fabric face mask with a coating containing both graphene and carbon nanomaterials [76]. This graphene coating provides a bacterial resistance (staphylococcus aureus bacteria) up to 99.95 % within 24 h and keeping the mask clean and fresh. In addition, this

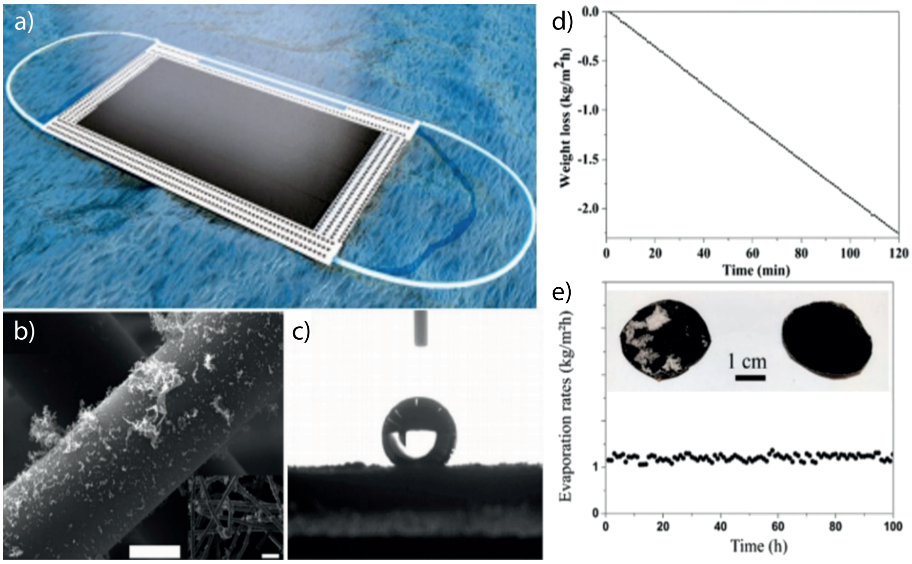

Figure 3. (a–e) Graphene-coated nonwoven fiber surgical mask. (a) Illustration, (b) SEM studies, scale bar is 10 μm. (c) water contact angle, (c) weight loss of 10 % saltwater under 1 sun intensity. (e) Top: Salt rejection performance capture photos of the polyimide after laser scribing after 24 h of desalination (left) and graphene coated mask after 100 h of destination (right). While the evaporation rated of the graphene coated mask under 1 sun intensity is at bottom. Reprinted with permission from Ref. [73], Copyright © 2020, American Chemical Society.

coating also repels dust and is effective against airborne particles of less than 2.5 microns in diameter. This mask can be washed and reused up to 10 times without losing its antibacterial or antistatic properties. Recently, LIGC Applications has developed graphene-based respirator mask called as "Guardian G-Volt" that can be sterilized and safely reused and they claimed to compete with gold standard N95 respirator masks [77]. This mask has advanced properties such as anti-static, repel dust, and effective against PM2.5 airborne particulates. It is interesting that fabric of the mask is washable and can be used up to 10 times without damage of graphene coating. Additionally, this Guardian G-Volt mask is allegedly 99 % efficient against particles larger than 0.3 microns and 80 % efficient against less than 0.3 microns. Beside this, the mask has an electrically embedded graphene filtration system formed from LIG, which can trap pathogens including COVID-19. The mask has potential for self-sterilization, by getting power from portable battery and also has an LED light system which alerts the user when mask needs to be replaced [77].

2.4 Decontamination, Degradation, and Filtration of COVID-19

COVID-19 have similar behavior like other members of coronavirus family such as MERS, SARS, etc. and remains active on the surface of metal, glass, plastic, etc. up to nine days after exposure. However, the survival time depends on the type of surface, environmental temperature, relative humidity, and specific strain of the virus. Already, several decontamination methods such as cleaning, degradation, disinfection, sanitization, sterilization, etc. are widely used against COVID-19 [12, 32, 78]. Beside this, a number of systems such as hydrogen peroxide decontamination (STERRAD Sterilization system), battle decontamination system, ultraviolet germicidal irradiation, ozone, photocatalytic oxidation, ion generation, and HEPA filters are used for the decontamination and disinfection of hospitals, airports, offices, parks, shopping areas, etc. [79]. These all materials, process and methods are successful up to some level, but most of them are not suitable for sensitive equipment especially in bio-medical area. Therefore, more smart materials and technologies should be introduced to save cost and time. In this regard, graphene-based nanomaterials can be ideal candidates for decontamination and disinfection of SARS-CoV-2. More recently, a self-sterilize graphene-based air filter has been developed [80]. The air filter is based on LIGs based on LIG; a conductive graphene foam is synthesized by using the heating surface of a common carbon material (polyimide-sheets) with industrial CO_2-based LASER Cutting (Figs. 4a–d). This filter has good potential to kill any microorganism including bacteria by using a joule heating mechanism, and the filter easily reached or greater than the 300 °C as shown in Figs. 4e–h. Additionally, it has also capacity to destroy other molecules and microorganism such as endotoxins, fungi, prions, spores, allergens, exotoxins, mycotoxins etc. This new technology concept can be used to integrate with advance air filtration system such as HEPA, air filtering in heating, ventilation, and air conditioning (HVAC) systems, self-sterilization of surgical and N-95 masks, and can be used to reduce nosocomial infection in hospitals. This new concept by integrating two technologies based on nano- and membrane technology could be effective against COVID-19.

Recent report that is presented for the current situation of SARS-CoV-2 in faecal, human wastewater generate a new problem for world. The SARS-CoV-2 has been identified and clinically confirmed in sewage in various countries such as Australia, Italy, France Netherland, and the U.S [81]. Effective wastewater treatment and as well as the minimization of transmission of infected wastewater is very important. Therefore, graphene-based membranes should be utilized for separation of viruses and bacteria from water. Previously proposed research has suggested that the graphene-based membranes are widely used to separation of ions, molecules, microorganism, and pathogens from water [33, 78, 82] by controlling their interlayer spacing. Therefore, it can be ideal candidate for the separation of COVID-19 from water. Up to date very less work has been done in this direction, therefore, we must set suitable direction to fabricate filter and membrane based on graphene for the separation of COVID-19 from water in future.

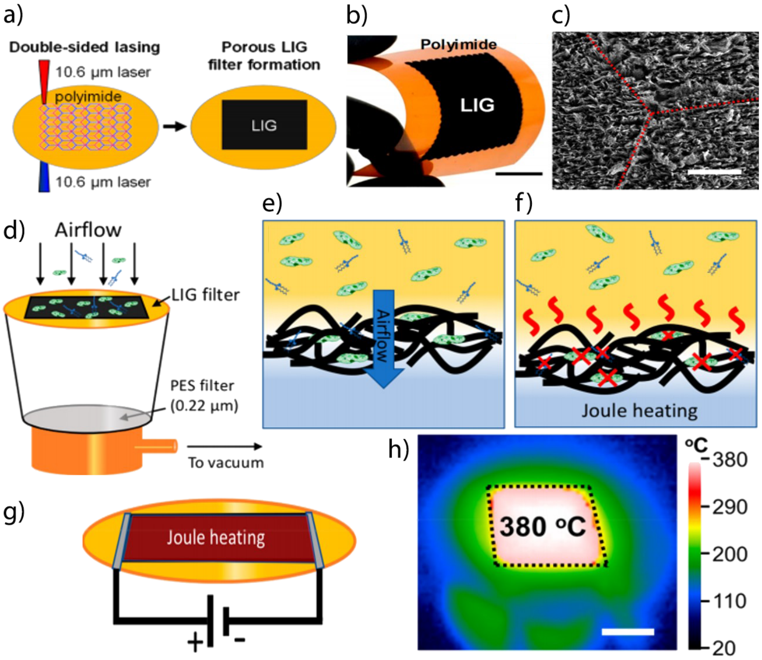

Figure 4. (a–c) Fabrication of LIG filter and characterization: (a) Schematic of the double-sided process, formation of LIG filter. (b) Optical image of LIG filter show the flexibility and mechanical properties. (c) SEM studies of LIG filter. (d) Air filtration process through LIG filter mounted on vacuum filtration with a backing PES test filter. Bacteria and endotoxins are suggested by picture. (e) Representation of filtration process followed by (f), sterilization, and depyrogenation through joule-heating mechanism. (g) Joule heating setup in which a potential across the filter for joule heating. (h) IR image of LIG filter at 380 °C. Black dotted lines show the shape of filter. Reprinted with permission from Ref. [82].

3 Challenges and Opportunities

In current situation, the research and technology development are the best weapon to fight against COVID-19 pandemic. Graphene-based nanomaterials have shown already some exciting results in bio-medical applications and have been widely explored for the biological activities. Therefore, graphene-based tools should be adapted for detection, diagnosis, decontamination, and prevention from this disease. Several graphene-based new products can be developed against COVID-19. Graphene-based gel or lotion can be prepared as decontaminating agent to kill COVID-19. In addition, graphene coated wipes can be perfect choice to disinfect the object's surfaces. The mist spray is also commonly used for human body sanitization and to clean any surface. Beside this, the virus that can also use as a nose or mouth spray to block the S-protein of SARS and COVID-19. The graphene-based nanodrugs conjugate with antivirals can be effective and successful formulation.

Graphene-coated PPE is essentially required to prevent aerosol transmission into hospitals and other infected area. In addition, air-purification and air-conditioning machines should be prepared to efficiently filter clean the COVID-19 and other respire germs present in air by introducing the multilayered graphene-based layers with modified positive charge filters. Furthermore, separation of SARS-CoV-2 from water can be possible using graphene-based filter membranes by tuning their microstructural properties and interlayer spacing. In addition, we can also prepare graphene-based photocatalyst, which can be used for inactivation and degradation of COVID-19 in water directly. Several studies have been reported on the photocatalytic inactivation of microorganisms. These photocatalyst can be used as good disinfectant against pathogens, which not only destroy them but also can be used sterilization [83–86]. Therefore, more work is needed to address these specific requirements concerning various exiting, and challenging applications in bio-medical science. Up to date, graphene-based nanomaterials is more promising candidate to fight against COVID-19, but we should focus on another 2D materials such as MXene, TMDCs, MOFs, COFs, h-BN, etc. This big 2D family could be an ideal platform against COVID-19 due to their interesting properties such as good conductivity, large surface area, layered structure, mechanical robust, flexibility, high affinity for guest materials. Therefore, more theoretical, and experimentally efforts are required to find most compatible material with graphene and other 2D materials for ideal biological properties against COVID-19.

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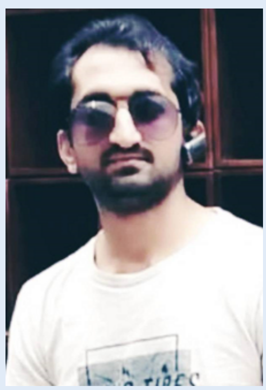
Conflicts of Interest

The authors declare no conflict of interest.



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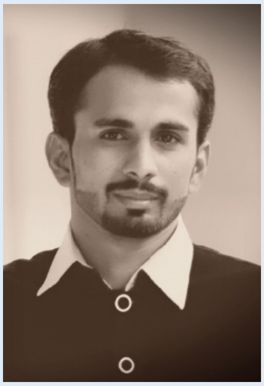

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Abbreviations

COFs	covalent organic frameworks
COVID-19	Coronavirus Disease 2019
FET	field-effect transistor
GO	graphene oxide
HEPA	high efficiency particulate air
LIG	laser-induced graphene
MOFs	metal-organic frameworks
MXene	metal carbide
PPE	personal protection equipment
rGO	reduced graphene oxide
RNA	ribonucleic acid
SARS	severe acute respiratory syndrome
TMDCs	transition metal dichalcogenides

References

[1] J. Chen, H. Lu, G. Melino, S. Boccia, M. Piacentini, W. Ricciardi, Y. Wang, Y. Shi, T. Zhu, *Cell Death Dis.* **2020**, *11*, 438. DOI: https://doi.org/10.1038/s41419-020-2603-0

[2] W. C. W. Chan, *ACS Nano* **2020**, *14*, 3719–3720. DOI: https://doi.org/10.1021/acsnano.0c02540

[3] S. M. Russell, A. Alba-Patiño, E. Barón, M. Borges, M. Gonzalez-Freire, R. de la Rica, *ACS Sensors* **2020**, *5*, 1506–1513. DOI: https://doi.org/10.1021/acssensors.0c00979

[4] G. Schett, B. Manger, D. Simon, R. Caporali, *Nat. Rev. Rheumatol.* **2020**, *16*, 465–470. DOI: https://doi.org/10.1038/s41584-020-0451-z

[5] C. M. S. Singal, P. Jaiswal, P. Seth, *ACS Chem. Neurosci.* **2020**, *11*, 1887–1899. DOI: https://doi.org/10.1021/acschemneuro.0c00251

[6] L. Liao, W. Xiao, M. Zhao, X. Yu, H. Wang, Q. Wang, S. Chu, Y. Cui, *ACS Nano* **2020**, *14*, 6348–6356. DOI: https://doi.org/10.1021/acsnano.0c03597

[7] C. Gil, T. Ginex, I. Maestro, V. Nozal, L. Barrado-Gil, M. Á. Cuesta-Geijo, J. Urquiza, D. Ramírez, C. Alonso, N. E. Cam-

pillo, A. Martinez, *J. Med. Chem.* **2020**, *63*, 12359–12386. DOI: https://doi.org/10.1021/acs.jmedchem.0c00606
[8] Q. Gao, L. Bao, H. Mao, L. Wang, K. Xu, M. Yang, Y. Li, L. Zhu, N. Wang, Z. Lv, H. Gao, X. Ge, B. Kan, Y. Hu, J. Liu, F. Cai, D. Jiang, Y. Yin, C. Qin, J. Li, X. Gong, X. Lou, W. Shi, D. Wu, H. Zhang, L. Zhu, W. Deng, Y. Li, J. Lu, C. Li, X. Wang, W. Yin, Y. Zhang, C. Qin, *Science* **2020**, *369*, 77–81. DOI: https://doi.org/10.1126/science.abc1932
[9] M. Kaur, S. Tiwari, R. Jain, *Sens. Bio-Sens. Res.* **2020**, *29*, 100362. DOI: https://doi.org/10.1016/j.sbsr.2020.100362
[10] R. Jalandra, A. K. Yadav, D. Verma, N. Dalal, M. Sharma, R. Singh, A. Kumar, P. R. Solanki, *Biomed. Pharmacother.* **2020**, *129*, 110446. DOI: https://doi.org/10.1016/j.biopha.2020.110446
[11] H. Huang, C. Fan, M. Li, H.-L. Nie, F.-B. Wang, H. Wang, R. Wang, J. Xia, X. Zheng, X. Zuo, J. Huang, *ACS Nano* **2020**, *14*, 3747–3754. DOI: https://doi.org/10.1021/acsnano.0c02618
[12] C. Weiss, M. Carriere, L. Fusco, I. Capua, J. A. Regla-Nava, M. Pasquali, J. A. Scott, F. Vitale, M. A. Unal, C. Mattevi, D. Bedognetti, A. Merkoçi, E. Tasciotti, A. Yilmazer, Y. Gogotsi, F. Stellacci, L. G. Delogu, *ACS Nano* **2020**, *14*, 6383–6406. DOI: https://doi.org/10.1021/acsnano.0c03697
[13] Y.-N. Chen, Y.-H. Hsueh, C.-T. Hsieh, D.-Y. Tzou, P.-L. Chang, *Int. J. Environ. Res. Public Health* **2016**, *13*, 430. DOI: https://doi.org/10.3390/ijerph13040430
[14] M. C. Sportelli, M. Izzi, *Nanomaterials* **2020**, *10*, 802. DOI: https://doi.org/10.3390/nano10040802
[15] S. Weatherby, J. M. Seddon, P. Ceroni, *Faraday Discuss.* **2020**, *222*, 8–9. DOI: https://doi.org/10.1039/D0FD90009E
[16] M. S. Mahmoud Nasrollahzadeh, Ghazaleh Jamalipour Soufi, Siavash Iravani, R. S. Varma, *Nanomaterials* **2020**, *10*, 1072. DOI: https://doi.org/10.3390/nano10061072
[17] C. I. Colino, C. G. Millán, J. M. Lanao, *Int. J. Mol. Sci.* **2018**, *19*, 1627. DOI: https://doi.org/10.3390/ijms19061627
[18] A. Khezerlou, M. Alizadeh-Sani, M. Azizi-Lalabadi, A. Ehsani, *Microb. Pathog.* **2018**, *123*, 505–526. DOI: https://doi.org/10.1016/j.micpath.2018.08.008
[19] A. Ali, M. Aamir, K. H. Thebo, J. Akhtar, *Chem. Rec.* **2020**, *20*, 344–354. DOI: https://doi.org/10.1002/tcr.201900024
[20] K. H. Thebo, X. Qian, Q. Zhang, L. Chen, H. M. Cheng, W. Ren, *Nat. Commun.* **2018**, *9*, 1486. DOI: https://doi.org/10.1038/s41467-018-03919-0
[21] X. Qian, L. Chen, L. Yin, Z. Liu, S. Pei, F. Li, G. Hou, S. Chen, L. Song, K. H. Thebo, H. M. Cheng, W. Ren, *Science* **2020**, *370*, 6516. DOI: https://doi.org/10.1126/science.abb9704
[22] A. Ali, R. Pothu, S. H. Siyal, S. Phulpoto, M. Sajjad, K. H. Thebo, *Mater. Sci. Energy Technol.* **2019**, *2*, 83–88. DOI: https://doi.org/10.1016/j.mset.2018.11.002
[23] H. W. Kim, H. W. Yoon, S.-M. Yoon, B. M. Yoo, B. K. Ahn, Y. H. Cho, H. J. Shin, H. Yang, U. Paik, S. Kwon, J.-Y. Choi, H. B. Park, *Science* **2013**, *342*, 91–95. DOI: https://doi.org/10.1126/science.1236098
[24] Q. Yang, Y. Su, C. Chi, C. T. Cherian, K. Huang, V. G. Kravets, F. C. Wang, J. C. Zhang, A. Pratt, A. N. Grigorenko, F. Guinea, A. K. Geim, R. R. Nair, *Nat. Mater.* **2017**, *16*, 1198. DOI: https://doi.org/10.1038/nmat5025
[25] M. Sun, M. Li, X. Zhang, C. Wu, Y. Wu, *Sep. Purif. Technol.* **2020**, *232*, 115963. DOI: https://doi.org/10.1016/j.seppur.2019.115963
[26] J. Abraham, K. S. Vasu, C. D. Williams, K. Gopinadhan, Y. Su, C. T. Cherian, J. Dix, E. Prestat, S. J. Haigh, I. V. Grigorieva, P. Carbone, A. K. Geim, R. R. Nair, *Nat. Nanotech.* **2017**, *12*, 546. DOI: https://doi.org/10.1038/nnano.2017.21
[27] Y. M. Lee, B. Jung, Y. H. Kim, A. R. Park, S. Han, W.-S. Choe, P. J. Yoo, *Adv. Mater.* **2014**, *26*, 3899–3904. DOI: https://doi.org/10.1002/adma.201305862
[28] K. H. Thebo, X. Qian, Q. Wei, Q. Zhang, H.-M. Cheng, W. Ren, *J. Mater. Sci. Technol.* **2018**, *34*, 1481–1486. DOI: https://doi.org/10.1016/j.jmst.2018.05.008
[29] Q. Zhang, X. Qian, K. H. Thebo, H.-M. Cheng, W. Ren, *Sci. Bull.* **2018**, *63*, 788–794. DOI: https://doi.org/10.1016/j.scib.2018.05.015
[30] C. H. A. Tsang, H. Y. H. Kwok, Z. Cheng, D. Y. C. Leung, *Prog. Solid State Chem.* **2017**, *45–46*, 1–8. DOI: https://doi.org/10.1016/j.progsolidstchem.2017.02.001
[31] V. Palmieri, M. Papi, *Nano Today* **2020**, *33*, 100883. DOI: https://doi.org/10.1016/j.nantod.2020.100883
[32] P. Kumar Raghav, S. Mohanty, *Medical Hypotheses* **2020**, *144*, 110031–110031. DOI: https://doi.org/10.1016/j.mehy.2020.110031
[33] Y. L. F. Musico, C. M. Santos, M. L. P. Dalida, D. F. Rodrigues, *ACS Sustainable Chem. Eng.* **2014**, *2*, 1559–1565. DOI: https://doi.org/10.1021/sc500044p
[34] L. Ji-Seon, K. Jungho, S. Hojeong, M. Dal-Hee, *2D Mater.* **2020**, *7*, 7044001. DOI: https://doi.org/10.1088/2053-1583/ab9a64
[35] N. A. Nahyoon, L. Liu, K. Rabe, K. H. Thebo, L. Yuan, J. Sun, F. Yang, *Electrochim. Acta* **2018**, *271*, 41–48. DOI: https://doi.org/10.1016/j.electacta.2018.03.109
[36] I. Chandio, F. A. Janjhi, A. A. Memon, S. Memon, Z. Ali, K. H. Thebo, A. A. A. Pirzado, A. A. Hakro, W. S. Khan, *Desalination* **2021**, *500*, 114848. DOI: https://doi.org/10.1016/j.desal.2020.114848
[37] F. Ahmed Janjhi, I. Chandio, A. Ali Memon, Z. Ahmed, K. Hussain Thebo, A. Ali Ayaz Pirzado, A. Ali Hakro, M. Iqbal, *Sep. Purif. Technol* **2020**, in Press. DOI: https://doi.org/10.1016/j.seppur.2020.117969
[38] S. Pei, Q. Wei, K. Huang, H. M. Cheng, W. Ren, *Nat. Commun.* **2018**, *9*, 145. DOI: https://doi.org/10.1038/s41467-017-02479-z
[39] S. Pei, H.-M. Cheng, *Carbon* **2012**, *50*, 3210–3228. DOI: https://doi.org/10.1016/j.carbon.2011.11.010
[40] A. Lukowiak, A. Kedziora, W. Strek, *Adv. Colloid Interface Sci.* **2016**, *236*, 101–112. DOI: https://doi.org/10.1016/j.cis.2016.08.002
[41] P. Innocenzi, L. Stagi, *Chem. Sci.* **2020**, *11*, 6606–6622. DOI: https://doi.org/10.1039/D0SC02658A
[42] S. Ye, K. Shao, Z. Li, N. Guo, Y. Zuo, Q. Li, Z. Lu, L. Chen, Q. He, H. Han, *ACS Appl. Mater. Interfaces* **2015**, *7*, 21571–21579. DOI: https://doi.org/10.1021/acsami.5b06876
[43] K. Tadyszak, J. K. Wychowaniec, J. Litowczenko, *Nanomaterials* **2018**, *8*, 944. DOI: https://doi.org/10.3390/nano8110944

[44] B. A. Ahidjo, M. W. C. Loe, Y. L. Ng, C. K. Mok, J. J. H. Chu, *ACS Infect. Dis.* **2020**, *6*, 1624–1634. DOI: https://doi.org/10.1021/acsinfecdis.0c00236

[45] X. Mei, H.-C. Lee, K.-y. Diao, M. Huang, B. Lin, C. Liu, Z. Xie, Y. Ma, P. M. Robson, M. Chung, A. Bernheim, V. Mani, C. Calcagno, K. Li, S. Li, H. Shan, J. Lv, T. Zhao, J. Xia, Q. Long, S. Steinberger, A. Jacobi, T. Deyer, M. Luksza, F. Liu, B. P. Little, Z. A. Fayad, Y. Yang, *Nat. Med.* **2020**, *26*, 1224–1228. DOI: https://doi.org/10.1038/s41591-020-0931-3

[46] W. Feng, A. M. Newbigging, C. Le, B. Pang, H. Peng, Y. Cao, J. Wu, G. Abbas, J. Song, D.-B. Wang, M. Cui, J. Tao, D. L. Tyrrell, X.-E. Zhang, H. Zhang, X. C. Le, *Anal. Chem.* **2020**, *92*, 15, 10196–10209. DOI: https://doi.org/10.1021/acs.analchem.0c02060

[47] B. Udugama, P. Kadhiresan, H. N. Kozlowski, A. Malekjahani, M. Osborne, V. Y. C. Li, H. Chen, S. Mubareka, J. B. Gubbay, W. C. W. Chan, *ACS Nano* **2020**, *14*, 3822–3835. DOI: https://doi.org/10.1021/acsnano.0c02624

[48] N. Bhalla, Y. Pan, Z. Yang, A. F. Payam, *ACS Nano* **2020**, *14*, 7, 7783–7807. DOI: https://doi.org/10.1021/acsnano.0c04421

[49] G. Qiu, Z. Gai, Y. Tao, J. Schmitt, G. A. Kullak-Ublick, J. Wang, *ACS Nano* **2020**, *14*, 5268–5277. DOI: https://doi.org/10.1021/acsnano.0c02439

[50] L. Zeng, Y. Li, J. Liu, L. Guo, Z. Wang, X. Xu, S. Song, C. Hao, L. Liu, M. Xin, C. Xu, *Mater. Chem. Front.* **2020**, *4*, 2000–2005. DOI: https://doi.org/10.1039/D0QM00294A

[51] P. Moitra, M. Alafeef, K. Dighe, M. B. Frieman, D. Pan, *ACS Nano* **2020**, *14*, 7617–7627. DOI: https://doi.org/10.1021/acsnano.0c03822

[52] E. Alphandéry, *Bioconjug. Chem.* **2020**, *31*, 8, 1873–1882. DOI: https://doi.org/10.1021/acs.bioconjchem.0c00287

[53] S. Kumar, W. Ahlawat, R. Kumar, N. Dilbaghi, *Biosens. Bioelectron.* **2015**, *70*, 498–503. DOI: https://doi.org/10.1016/j.bios.2015.03.062

[54] G. Seo, G. Lee, M. J. Kim, S.-H. Baek, M. Choi, K. B. Ku, C.-S. Lee, S. Jun, D. Park, H. G. Kim, S.-J. Kim, J.-O. Lee, B. T. Kim, E. C. Park, S. I. Kim, *ACS Nano* **2020**, *14*, 5135–5142. DOI: https://doi.org/10.1021/acsnano.0c02823

[55] A. Cordaro, G. Neri, M. T. Sciortino, A. Scala, A. Piperno, *Nanomaterials* **2020**, *10*, 1014. DOI: https://doi.org/10.3390/nano10061014

[56] N. A. S. Omar, Y. W. Fen, J. Abdullah, A. R. Sadrolhosseini, Y. Mustapha Kamil, N. '. M. Fauzi, H. S. Hashim, M. A. Mahdi, *Nanomaterials* **2020**, *10*, 569. DOI: https://doi.org/10.3390/nano10030569

[57] Y. Zhang, X. Chen, G. M. Roozbahani, X. Guan, *Anal. Bioanal. Chem.* **2018**, *410*, 6177–6185. DOI: https://doi.org/10.1007/s00216-018-1224-2

[58] K. Rasool, M. Helal, A. Ali, C. E. Ren, Y. Gogotsi, K. A. Mahmoud, *ACS Nano* **2016**, *10*, 3674–3684. DOI: https://doi.org/10.1021/acsnano.6b00181

[59] K. Rasool, K. A. Mahmoud, D. J. Johnson, M. Helal, G. R. Berdiyorov, Y. Gogotsi, *Sci. Rep.* **2017**, *7*, 1598. DOI: https://doi.org/10.1038/s41598-017-01714-3

[60] M. Ikram, R. Tabassum, U. Qumar, S. Ali, A. Ul-Hamid, A. Haider, A. Raza, M. Imran and S. Ali, *RSC Adv.* **2020**, *10*, 20559–20571. DOI: https://doi.org/10.1039/D0RA02458A

[61] X. Cao, C. Ding, C. Zhang, W. Gu, Y. Yan, X. Shi, Y. Xian, *J Mater. Chem. B* **2018**, *6*, 8011–8036. DOI: https://doi.org/10.1039/C8TB02519C

[62] S. Zhu, L. Gong, J. Xie, Z. Gu, Y. Zhao, *Small Methods* **2017**, *1*, 1700220. DOI: https://doi.org/10.1002/smtd.201700220

[63] A. Mukheem, S. Shahabuddin, N. Akbar, A. Miskon, N. Muhamad Sarih, K. Sudesh, N. Ahmed Khan, R. Saidur, N. Sridewi, *Nanomaterials* **2019**, *9*, 645. DOI: https://doi.org/10.3390/nano9040645

[64] M. Shen, F. Forghani, X. Kong, D. Liu, X. Ye, S. Chen, T. Ding, *Compr. Rev. Food Sci. Food Saf.* **2020**, *19*, 1397–1419. DOI: https://doi.org/10.1111/1541-4337.12515

[65] N. Bhardwaj, S. K. Pandey, J. Mehta, S. K. Bhardwaj, K.-H. Kim, A. Deep, *Toxicol. Res.* **2018**, *7*, 931–941. DOI: https://doi.org/10.1039/C8TX00087E

[66] P. Cao, X. Wu, W. Zhang, L. Zhao, W. Sun, Z. Tang, *Ind. Eng. Chem. Res.* **2020**, *59*, 1559–1567. DOI: https://doi.org/10.1021/acs.iecr.9b05659

[67] G. Wyszogrodzka, B. Marszałek, B. Gil, P. Dorożyński, *Drug Discovery Today* **2016**, *21*, 1009–1018. DOI: https://doi.org/10.1016/j.drudis.2016.04.009

[68] P. Cheng, Y. Chen, X. Yan, Y. Wang, W.-Z. Lang, *ChemSusChem.* **2019**, *12*, 275–282. DOI: https://doi.org/10.1002/cssc.201802235

[69] M. Tebyetekerwa, Z. Xu, S. Yang, S. Ramakrishna, *Adv. Fiber Mater.* **2020**, *2*, 161–166. DOI: https://doi.org/10.1007/s42765-020-00049-5

[70] S. R. Lustig, J. J. H. Biswakarma, D. Rana, S. H. Tilford, W. Hu, M. Su, M. S. Rosenblatt, *ACS Nano* **2020**, *14*, 7651–7658. DOI: https://doi.org/10.1021/acsnano.0c03972

[71] N. El-Atab, N. Qaiser, H. Badghaish, S. F. Shaikh, M. M. Hussain, *ACS Nano* **2020**, *14*, 7659–7665. DOI: https://doi.org/10.1021/acsnano.0c03976

[72] S. Kumar, R. Nyodu, V. K. Maurya, S. K. Saxena, in *Coronavirus Disease 2019 (COVID-19): Epidemiology, Pathogenesis, Diagnosis, and Therapeutics*, (Ed: S. K. Saxena), Springer Singapore, Singapore **2020**, 23–31.

[73] H. Zhong, Z. Zhu, J. Lin, C. F. Cheung, V. L. Lu, F. Yan, C.-Y. Chan, G. Li, *ACS Nano* **2020**, *14*, 6213–6221. DOI: https://doi.org/10.1021/acsnano.0c02250

[74] www.bonbouton.com/graphene-mask (Accessed on December 03, 2020)

[75] https://statnano.com/news/67657/A-COVID-19-Virucidal-Graphene-based-Composite-Ink-for-More-Effective-PPE (Accessed on May 27, 2020)

[76] www.planartech.com/store/p1/graphene-enhanced-face-mask-pack-of-3.html (Accessed on October 02, 2020)

[77] https://grapheneindustry.org.au/2020/05/g-volt-mask/ (Accessed on May 11, 2020)

[78] Z. Song, X. Wang, G. Zhu, Q. Nian, H. Zhou, D. Yang, C. Qin, R. Tang, *Small* **2015**, *11*, 1171–1176. DOI: https://doi.org/10.1002/smll.201401706

[79] A. E. Torres, A. B. Lyons, S. Narla, I. Kohli, A. Parks-Miller, D. Ozog, I. H. Hamzavi, H. W. Lim, *Photochem. Photobiol. Sci.* **2020**, *19*, 746–751. DOI: https://doi.org/10.1039/D0PP00131G

[80] M. G. Stanford, J. T. Li, Y. Chen, E. A. McHugh, A. Liopo, H. Xiao, J. M. Tour, *ACS Nano* **2019**, *13*, 11912–11920. DOI: https://doi.org/10.1021/acsnano.9b05983

[81] M. Usman, M. Farooq, K. Hanna, *Environ. Sci. Technol.* **2020**, *54*, 7758–7759. DOI: https://doi.org/10.1021/acs.est.0c02777

[82] K. A. Mahmoud, B. Mansoor, A. Mansour, M. Khraisheh, *Desalination* **2015**, *356*, 208–225. DOI: https://doi.org/10.1016/j.desal.2014.10.022

[83] Y. Deng, Z. Li, R. Tang, K. Ouyang, C. Liao, Y. Fang, C. Ding, L. Yang, L. Su, D. Gong, *Environ. Sci. Nano* **2020**, *7*, 702–723. DOI: https://doi.org/10.1039/C9EN01318K

[84] R. Nakano, H. Ishiguro, Y. Yao, J. Kajioka, A. Fujishima, K. Sunada, M. Minoshima, K. Hashimoto, Y. Kubota, *Photochem. Photobiol. Sci.* **2012**, *11*, 1293–1298. DOI: https://doi.org/10.1039/C2PP05414K

[85] Y. Yamaguchi, T. Shimodo, S. Usuki, K. Torigoe, C. Terashima, K.-i. Katsumata, M. Ikekita, A. Fujishima, H. Sakai, K. Nakata, *Photochem. Photobiol. Sci.* **2016**, *15*, 988–994. DOI: https://doi.org/10.1039/C6PP00093B

[86] Z. Ahmed, F. Rehman, U. Ali, A. Ali, M. Iqbal, K. H. Thebo, *ChemBioEng Rev.* **2021**, *8 (2)*.

